Long-Term Electricity Supply and Demand Projection upto 2050 in Bangladesh – A LEAP Based Scenario Analysis

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A Thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in Mechanical Engineering

Department of Mechanical and Production Engineering (MPE)

Islamic University of Technology (IUT)

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Candidate's Declaration

This is to certify that the work presented in this thesis, titled, "Long-Term Electricity Supply and Demand Projection upto 2050 in Bangladesh – A LEAP Based Scenario Analysis", is the outcome of the investigation and research carried out by us under the supervision of Dr. M. Ahsan Habib, Professor, MPE Department.

It is also declared that neither this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma.

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Recommendation of the Thesis Supervisors

The thesis titled "Long-Term Electricity Supply and Demand Projection upto 2050 in Bangladesh – A LEAP Based Scenario Analysis" submitted by Shafique Ahmed Rahib, Student No: 20011113 and Azmain Kabir, Student No: 200011124 has been accepted as satisfactory in partial fulfillment of the requirements for the degree of B Sc. in Mechanical Engineering **on 29th September, 2025.**

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CO-PO Mapping of ME 4800 -Theis and Project

COs	Course Outcomes (CO) Statement	(PO)	Addressed by	
CO1	Discover and Locate research problems and illustrate them via figures/tables or projections/ideas through field visit and literature review and determine/Setting aim and objectives of the project/work/research in specific, measurable, achievable, realistic and timeframe manner.	**PO2 Problem analysis**	Thesis Book	√
			Performance by research	√
			Presentation and soft skill	√
CO2	Design research solutions of the problems towards achieving the objectives and its application. Design systems, components or processes that meets related needs in the field of mechanical engineering	**PO3 Design/development of solutions**	Thesis Book	√
			Performance by research	√
			Presentation and soft skill	√
CO3	Review, debate, compare and contrast the relevant literature contents. Relevance of this research/study. Methods, tools, and techniques used by past researchers and justification of use of them in this work.	**PO4 Investigation**	Thesis Book	√
			Performance by research	√
			Presentation and soft skill	√
CO4	Analyse data and exhibit results using tables, diagrams, graphs with their interpretation. Investigate the designed solutions to solve the problems through case study/survey study/experimentation/simulation using modern tools and techniques.	**PO5 Modern tool usage**	Thesis Book	√
			Performance by research	√
			Presentation and soft skill	√
CO5	Apply moral values and research/professional ethics throughout the work, and justify genuine referencing on sources, and demonstration of own contribution.	**PO8 Ethics**	Thesis Book	√
			Performance by research	√
			Presentation and soft skill	√
CO6	Perform own self and manage group activities from the beginning to the end of the research/work as a quality work.	**PO9 Individual work and teamwork**	Thesis Book	√
			Performance by research	√
			Presentation and soft skill	√
CO7	Compile and arrange the work outputs, write the report/thesis, a sample journal paper, and present the work to wider audience using modern communication tools and techniques.	**PO10 Communication**	Thesis Book	√
			Performance by research	
			Presentation and soft skill	
CO8	Recognize the necessity of life-long learning in career development in dynamic real-world situations from the experience of completing this project.	**PO12 Life-long learning**	Thesis Book	
			Performance by research	√
			Presentation and soft skill	

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K-P-A Mapping of ME 4800 -Thesis and Project

COs	POs	Related Ks								Related Ps							Related As				
		K1	K2	K3	K4	K5	K6	K7	K8	P1	P2	P3	P4	P5	P6	P7	A1	A2	A3	A4	A5
CO1	PO2	√		√				√		√	√				√	√					√
CO2	PO3		√		√		√	√				√	√	√	√	√				√	√
CO3	PO4		√	√		√		√	√		√	√		√					√		√
CO4	PO5					√	√	√					√	√							√
CO5	PO8		√						√						√		√				√
CO6	PO9						√				√				√	√		√			√
CO7	PO10						√								√	√					√
CO8	PO12								√		√								√	√	

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Signature of the Supervisor

Name of the Supervisor: Prof. Dr M Ahsan Habib

List of Sustainable Development Goals (SDGs) Addressed in this Project

SDG No.	Goals	Targets	Relevance to the Thesis	Remarks
1	No Poverty	1.1 Eradicate extreme poverty (people living on less than $1.25/day).		
		1.2 Reduce poverty in all its forms by at least half.		
		1.3 Implement nationally appropriate social protection systems.		
		1.4 Ensure equal rights to economic resources, services, property, inheritance, technology, and financial services.	√	Inclusive access to modern energy modeled as an enabler of services and jobs.
		1.5 Build resilience of the poor and reduce exposure to climate-related and other shocks.	√	Reliability and resilience metrics used to reduce outage-related shocks to livelihoods.
		1.a Mobilize resources to end poverty.	√	Quantifies public-sector investment needs for grid upgrades and efficiency programs.
		1.b Create pro-poor policy frameworks.	√	Scenario design follows pro-poor policy framing (affordability, reliability, access).
2	Zero Hunger	2.1 End hunger and ensure access to safe, nutritious food year-round.		
		2.2 End all forms of malnutrition.		
		2.3 Double agricultural productivity and incomes of small-scale producers.		
		2.4 Ensure sustainable food production systems and resilient agricultural practices.		
		2.5 Maintain genetic diversity of seeds, plants, and animals.		
		2.a Increase investment in rural infrastructure, research, and technology.	√	Strengthens rural electrification and feeder upgrades; supports productive use and local research capacity through data-driven planning.

		2.b Correct and prevent trade restrictions/distortions in global food markets.		
		2.c Adopt measures to ensure proper functioning of food commodity markets.		
3	Good Health and Well Being	3.1 Reduce global maternal mortality ratio.		
		3.2 End preventable deaths of newborns and under-5 children.		
		3.3 End epidemics of AIDS, tuberculosis, malaria, and neglected tropical diseases.		
		3.4 Reduce premature mortality from NCDs and promote mental health.		
		3.5 Strengthen prevention and treatment of substance abuse.		
		3.6 Halve global deaths/injuries from road traffic accidents.		
		3.7 Ensure universal access to sexual and reproductive healthcare.		
		3.8 Achieve universal health coverage.		
		3.9 Reducedeaths from hazardous chemicals, pollution, and contamination.	√	Cleaner generation mix and efficiency measures lower power-sector emissions, improving ambient air quality exposure.
		3.a Strengthen tobacco control (WHO FCTC).		
		3.b Support R&D of vaccines and medicines.		
		3.c Increase health financing and workforce.		
		3.d Strengthen capacity for early warning and risk management.	√	Scenario analysis and reliability margins inform contingency planning for fuel shocks, outages, and climate-related risks.

4	Quality Education	4.1 Ensure all complete free, equitable, quality primary and secondary education.		
		4.2 Ensure access to quality early childhood development and pre-primary education.		
		4.3 Ensure equal access to affordable technical, vocational, and higher education.		
		4.4 Increase skills for employment and entrepreneurship.	√	Work builds practical skills in energy data, LEAP modeling, and evidence-based planning useful for green jobs and startups.
		4.5 Eliminate gender disparities in education.		
		4.6 Ensure literacy and numeracy for youth and adults.		
		4.7 Ensure learners acquire knowledge/skills for sustainable development.	√	The thesis develops literacy in scenario design, resource efficiency, and evidence-based power-sector decisions.
		4.a Build and upgrade education facilities that are inclusive and safe.		
		4.b Expand scholarships for developing countries.		
		4.c Increase supply of qualified teachers.		
5	Gender Equality	5.1 End all forms of discrimination against women and girls.		
		5.2 Eliminate violence against women and girls.		
		5.3 Eliminate harmful practices (child, early, forced marriage, FGM).		
		5.4 Recognize and value unpaid care and domestic work.		

		5.5 Ensure women’s participation in leadership and decision-making.		
		5.6 Ensure universal access to reproductive health and rights.		
		5.a Undertake reforms to give women equal rights to resources.		
		5.b Enhance use of enabling technology to empower women.		
		5.c Adopt and strengthen policies and laws for gender equality.		
6	Clean Water and Sanitation	6.1 Achieve universal and equitable access to safe drinking water.		
		6.2 Achieve access to adequate sanitation and hygiene.		
		6.3 Improve water quality by reducing pollution.		
		6.4 Increase water-use efficiency and sustainable withdrawals.	√	Lower T&D losses and higher efficiency/RE shares reduce water intensity of electricity supply.
		6.5 Implement integrated water resources management.	√	Power-sector scenarios support integrated resource planning that considers plant siting, hydro seasonality, and water constraints.
		6.6 Protect and restore water-related ecosystems.	√	Shifting away from water-intensive thermal generation and improving efficiency helps ease pressure on rivers and wetlands.
		6.a Expand international cooperation in water and sanitation.		
		6.b Support participation of local communities.		
7	Affordable and Clean Energy	7.1 Ensure universal access to affordable, reliable, modern energy services.	√	Moderate Transition pathways with grid upgrades and efficiency measures improve

				reliability and keep end-user costs manageable.
		7.2 Increase substantially the share of renewable energy.		
		7.3 Double global rate of improvement in energy efficiency.	√	Demand moderation is achieved by efficiency assumptions across sectors and targeted T&D loss cuts.
		7.a Enhance international cooperation on clean energy research/technology.	√	The work adopts global best-practice methods (LEAP scenarios, benchmarking) to guide domestic clean-energy uptake.
		7.b Expand infrastructure and upgrade technology for sustainable energy.	√	Results prioritize grid reinforcement, flexible generation, and smarter operations to integrate cleaner supply.
8	Decent Work and Economic Growth	8.1 Sustain per capita economic growth.		
		8.2 Achieve higher levels of productivity through diversification, tech, and innovation.	√	More reliable electricity and evidence-based planning support industrial productivity and tech-driven growth.
		8.3 Promote policies for decent job creation and entrepreneurship.		
		8.4 Improve resource efficiency in production and consumption.	√	Efficiency measures and DSM lower energy intensity per unit of output and reduce wasteful consumption.
		8.5 Achieve full and productive employment for all.		
		8.6 Substantially reduce youth not in employment/education/training.		
		8.7 Eradicate forced labour, modern slavery, and child labour.		
		8.8 Protect labour rights and safe working environments.		

		8.9 Promote sustainable tourism.		
		8.a Increase aid for trade support.		
		8.b Develop a global youth employment strategy.		
9	Industry, Innovation and Infrastructure	9.1 Develop quality, reliable, sustainable infrastructure.	√	Roadmaps point to least-cost grid investments that improve service quality and resilience.
		9.2 Promote inclusive and sustainable industrialization.	√	Cleaner, steadier power enables expansion of manufacturing while curbing emissions and local pollutants.
		9.3 Increase access of SMEs to financial services and integration into value chains.		
		9.4 Upgrade infrastructure for sustainability and resource efficiency.	√	Recommended actions modernize networks and shift the generation mix toward lower-intensity options.
		9.5 Enhance scientific research and technology development.	√	The thesis builds national capability in energy systems modeling, data handling, and scenario analytics.
		9.a Facilitate sustainable infrastructure in developing countries.	√	Outputs translate into investment-ready priorities for donors and PPP programs in power sector upgrades.
		9.b Support domestic tech development and value addition.		
		9.c Increase access to ICT and internet.		
10	Reduced Inequalities	10.1 Achieve income growth of bottom 40%.		
		10.2 Empower and promote inclusion regardless of status.		

		10.3 Ensure equal opportunity and reduce inequalities of outcome.		
		10.4 Adopt policies for fiscal, wage, and social protection equality.		
		10.5 Improve regulation of global financial markets.		
		10.6 Ensure enhanced representation in global institutions.		
		10.7 Facilitate safe, regular, and responsible migration.		
		10.a Implement special treatment for developing countries.		
		10.b Encourage development assistance and investment in least developed areas.		
		10.c Reduce remittance costs.		
11	Sustainable Cities and Communities	11.1 Ensure access to adequate, safe, and affordable housing.		
		11.2 Provide sustainable transport systems.	√	
		11.3 Enhance inclusive urbanization and capacity for planning.		
		11.4 Protect cultural and natural heritage.		
		11.5 Reduce disaster impact and losses.		
		11.6 Reduce environmental impact of cities (air quality, waste).	√	Scenario pathways cut urban air-quality burdens by moderating oil use in city-adjacent peaker plants and prioritizing efficiency/DSM, which lowers local emissions per kWh.
		11.7 Provide access to safe, inclusive green/public spaces.		

		11.a Support positive links between urban, peri-urban, rural.		
		11.b Increase disaster risk reduction strategies.	√	Stress-testing fuel shocks and outages in LEAP informs contingency margins, reserve needs, and siting choices that improve grid resilience for urban areas.
		11.c Support least developed countries in sustainable building.		
12	Responsible Consumption and Production	12.1 Implement 10-Year Framework on sustainable consumption/production.		
		12.2 Achieve sustainable management and use of resources.	√	
		12.3 Halve per capita global food waste.		
		12.4 Manage chemicals and waste sustainably.	√	Lower fuel oil dependence and improved O&M practices reduce handling/disposing of hazardous by-products in generation.
		12.5 Substantially reduce waste generation.	√	Efficiency measures and loss reduction curb fuel use and associated waste across the supply chain.
		12.6 Encourage companies to adopt sustainable practices.	√	Utility and IPP guidance favors higher-efficiency units, cleaner fuels, and monitoring of plant-level emissions/intensity.
		12.7 Promote sustainable public procurement.	√	Recommends procuring high-efficiency equipment (e.g., transformers, motors) and cleaner capacity additions in public tenders.
		12.8 Ensure people have relevant information for sustainable development.	√	The study’s transparent assumptions, datasets, and scenario dashboards support informed decision-making by planners and stakeholders.

		12.a Support developing countries' scientific and technological capacity.		
		12.b Develop tools to monitor sustainable tourism impacts.		
		12.c Rationalize inefficient fossil-fuel subsidies.		
13	Climate Action	13.1 Strengthen resilience and adaptive capacity to climate-related hazards.		
		13.2 Integrate climate measures into national policies.	√	The Moderate Transition pathway aligns capacity mix and demand-side actions with Bangladesh's NDC envelopes and medium-term plans.
		13.3 Improve education and awareness on climate change.	√	The thesis distills results for non-technical audiences and policy briefings, building literacy on emissions–energy trade-offs.
		13.a Implement UNFCCC commitments (mobilize $100 billion annually).		
		13.b Promote mechanisms for capacity- building in least developed countries.		
14	Life Below Water	14.1 Reduce marine pollution.		
		14.2 Sustainably manage and protect marine ecosystems.		
		14.3 Minimize and addressocean acidification.		
		14.4 Regulate harvesting and end overfishing.		
		14.5 Conserve at least 10% of coastal and marine areas.		
		14.6 Prohibit harmful fisheries subsidies.		
		14.7 Increase economic benefits from sustainable marine resources.		

		14.a Increase scientific knowledge and marine technology transfer.		
		14.b Provide access for small-scale artisanal fishers.		
		14.c Implement international law for oceans.		
15	Life on Land	15.1 Conserve terrestrial and freshwater ecosystems.		
		15.2 Promote sustainable management of forests.		
		15.3 Combat desertification and restore degraded land.		
		15.4 Ensure conservation of mountain ecosystems.		
		15.5 Take urgent action to reduce biodiversity loss.		
		15.6 Promote fair benefit-sharing from genetic resources.		
		15.7 End poaching and trafficking of protected species.		
		15.8 Prevent introduction of invasive alien species.		
		15.9 Integrate ecosystem values into policies/planning.		
		15.a Mobilize resources for biodiversity.		
		15.b Finance sustainable forest management.		
		15.c Support local communities for forest and wildlife.		
16	Peace, Justice and Strong Institutions	16.1 Reduce violence and related death rates.		
		16.2 End abuse, trafficking, and violence against children.		
		16.3 Promote rules of law and equal access to justice.		

		16.4 Reduce illicit financial/arms flows, organized crime.		
		16.5 Reduce corruption and bribery.		
		16.6 Develop effective, accountable institutions.		
		16.7 Ensure inclusive, participatory decision-making.		
		16.8 Broaden participation of developing countries in global governance.		
		16.9 Provide legal identity for all (including birth registration).		
		16.10 Ensure access to information and protect freedoms.		
		16.a Strengthen national institutions for prevention of violence.		
		16.b Promote/enforce non-discriminatory laws and policies.		
17	Partnerships for the Goals	17.1 Strengthen domestic resource mobilization.		
		17.2 Developed countries to implement ODA commitments.		
		17.3 Mobilize additional financial resources.		
		17.4 Assist developing countries with debt sustainability.		
		17.5 Invest in least developed countries.		
		17.6 Enhance access to science, technology, innovation.		
		17.7 Promote environmentally sound technologies.		
		17.8 Fully operationalize technology bank for LDCs.		
		17.9 Enhance international support for capacity-		

		building.		
		17.10 Promote a universal, rules-based trading system (WTO).		
		17.11 Increase exports of developing countries.		
		17.12 Timely implementation of duty-free, quota-free market access.		
		17.13 Enhance global macroeconomic stability.		
		17.14 Enhance policy coherence for sustainable development.	√	Scenario-based results provide an evidence base to align power-sector targets (RE share, efficiency, gas strategy) with national plans, improving consistency across policies.
		17.15 Respect national policy space.		
		17.16 Enhance global partnerships.	√	Methods and assumptions are transparent and portable (LEAP model, sector datasets), enabling collaboration with government agencies, utilities, and research partners on aligned transition pathways.
		17.17 Encourage multi-stakeholder partnerships.		
		17.18 Enhance data capacity of developing countries.	√	The study compiles structured demand/supply data and reproducible LEAP files, which can be adopted as templates and training material for future national energy-planning exercises.
		17.19 Support capacity-building for sustainable development indicators.		

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We first express our sincere gratitude to our supervisor, Prof. Dr. M. Ahsan Habib, Head, Department of Mechanical & Production Engineering (MPE), Islamic University of Technology (IUT), for his steady guidance and thoughtful feedback throughout this work. We also thank Dr. Arafat Ahmed Bhuiyan, Professor, Department of MPE, IUT, for offering this topic and the opportunity to pursue it. Our appreciation extends to Mr. Sifat Abdul Bari, Lecturer, Department of MPE, IUT, for his practical support with the LEAP software and modeling workflow. We are grateful to the Department of MPE, IUT, for academic support and facilities, and to the library and lab staff for their cooperation. We acknowledge data and publications from BPDB, Power Division, SREDA, Petrobangla, and the Bangladesh Bureau of Statistics, which informed scenario design and validation. We also thank our classmates, friends, and families for their encouragement. Any remaining shortcomings are our own.

Abstract

This thesis examines the potential evolution of electricity demand, the generation mix, and associated emissions in Bangladesh through to 2050. The analysis is conducted using the LEAP modeling platform, focusing exclusively on the electricity sector. Four future scenarios are evaluated: Business-as-Usual (BAU), Accelerated Development (ADS), Low-Emission Sustainability (LESS), and Moderate Transition (MTS). The model first validates data from 2013–2022 against official statistics, after which trends are projected based on scenario-specific assumptions for population growth, GDP, electrification, and technology adoption. The power generation mix in the model includes combined-cycle gas, steam, and oil-fired plants, with solar and nuclear power contributions incorporated through capacity and generation projections. Emissions of CO_2, CO, CH_4, and NO_x are calculated using LEAP's Effects framework. Across all scenarios, electricity demand is projected to grow, but the timing and magnitude of emissions peaks differ. The BAU scenario maintains a reliance on older, oil-intensive generation, resulting in the highest cumulative emissions. The ADS scenario expands capacity rapidly, creating a sharp emissions peak in the late 2020s, followed by a decline as more efficient plants replace legacy units. The LESS scenario achieves the lowest emissions by 2050 through accelerated efficiency improvements and a cleaner energy supply, though it is the most challenging to implement. The MTS scenario provides a balanced outcome, with an earlier emissions peak and gradual decline, placing it between BAU and LESS in terms of both cumulative emissions and fossil fuel capacity. Given Bangladesh's current constraints, the MTS pathway offers a practical approach that yields meaningful and credible emission reductions.

Summary

A realistic computer model was developed to assess how reliable electricity supply could be ensured in Bangladesh while simultaneously reducing emissions from power plants. Four distinct pathways were tested to explore different approaches to balancing electricity demand and emissions reduction. In the Business-as-Usual (BAU) scenario, continued reliance on older, oil-fired power plants is assumed, resulting in a steady rise in both electricity demand and emissions over time.

The Accelerated Development (ADS) scenario assumes rapid capacity expansions, leading to an earlier peak in emissions, followed by a significant decline as newer, cleaner plants gradually replace outdated and inefficient units. In the Low-Emission Sustainability (LESS) scenario, a strong focus on efficiency improvements and a shift toward cleaner energy sources is modeled, yielding the greatest emissions reduction by 2050. However, this pathway demands the most substantial institutional commitment and investment to achieve.

The Moderate Transition Scenario (MTS) strikes a more balanced approach: inefficient plants are systematically retired, while efficient gas plants and renewable energy sources are prioritized. New capacity is added gradually, ensuring that electricity supply remains reliable while emissions are reduced relative to BAU. The MTS pathway offers a feasible and practical solution for Bangladesh, achieving a meaningful reduction in emissions without compromising the reliability of the power supply. This trajectory presents a more realistic and attainable path toward a sustainable energy future, aligning with both environmental goals and the country’s development constraints.

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Nomenclatures and Symbol

Abbreviation	Meaning
BAU	Business as Usual
ADS	Accelerated Development Scenario
LESS	Low-Emission Sustainability Scenario
MTS	Moderate Transition Scenario
LEAP	Long-range Energy Alternatives Planning
CCGT	Combined Cycle Gas Turbine
ST	Steam Turbine
RE	Renewable Energy
VRE	Variable Renewable Energy
LNG	Liquefied Natural Gas
T&D	Transmission and Distribution
PSMP	Power System Master Plan
IEPMP	Integrated Energy and Power Master Plan
MCPP	Mujib Climate Prosperity Plan
NDC	Nationally Determined Contribution
BPDB	Bangladesh Power Development Board
PDB	Power Development Board
SDG	Sustainable Development Goal

List of symbols:

kWh	kilowatt-hour
GWh	gigawatt-hour
MW	megawatt
GW	gigawatt
TJ	terajoule
toe	tonne of oil equivalent
t	tonne
kt	kilotonne
Mt	megatonne
CO_2	carbon dioxide
CO	carbon monoxide
CH_4	methane
NO_x	nitrogen oxides
%	percent

Chapter 1: Introduction

1.1 Introduction

This chapter outlines the context and motivation for studying electricity demand forecasting in Bangladesh. With rapid economic growth and rising electricity demand, long-term energy planning is crucial for a reliable power supply. It provides an overview of Bangladesh's energy challenges, the need for accurate load forecasting, and the role of the LEAP model in predicting future demand across various sectors. The chapter also presents the study's objectives and methodology, setting the stage for the following chapters.

1.1 Background

Bangladesh, as a fast-growing country, confronts considerable hurdles in addressing rising energy demand. The country has experienced exceptional economic progress in recent decades. As a result, electricity demand has increased at a quicker rate, with load shedding and power outages becoming commonplace, particularly during peak demand periods. GDP growth is heavily influenced by a country's long-term energy security, which is intricately linked to its energy market.

1.2 Importance of Accurate Load Forecasting

One of the most important components of managing the country's energy resources is forecasting future electricity requirements across various sectors. Accurate load forecasting is critical for creating long-term energy production, distribution, and infrastructure plans. In Bangladesh, where power generation capacity is limited, accurate demand forecasting is a necessity for ensuring a steady and reliable electricity supply.

1.3 Objectives of the Study

This work focuses on using the Long-range Energy Alternatives Planning (LEAP) system to predict the future electricity load for each sector in Bangladesh, including residential, industrial, commercial & public sectors, agriculture, and transportation. By utilizing LEAP, this study will provide insights into future electricity demand trends and help identify the most effective policy measures to ensure a balanced supply and demand for electricity in the coming decades.

1.4 Goals of the Study

1.4.1 LEAP Model Development

The first goal of this project is to develop a data-driven LEAP model specifically for Bangladesh. This model will simulate power demand and supply in a variety of sectors, including residential, industrial, commercial, public sectors, agriculture, and transportation. The focus will be on using historical data from sources such as BPDB annual reports, power usage statistics, population growth, and economic indicators to create a robust model that can forecast future electricity demand. This model will serve as a tool for policymakers to understand how power demand and supply may evolve, helping forecast future energy gaps and identify key areas for intervention.

1.4.2 Scenario-Based Analysis

The second objective is to conduct scenario-based analyses to explore potential trajectories of electricity demand and supply in Bangladesh through 2050. Scenarios such as Business-as-Usual (BAU), Accelerated Development (ADS), Moderate Transition (MTS), and Low-Emission Sustainability (LESS) will be developed, incorporating assumptions on economic growth, population, technology, and policy. These simulations will assess the range of possible demand and supply outcomes, offering insights into the future of Bangladesh's energy sector.

Chapter 2: Literature Review

2.1 Introduction

This section reviews the existing literature on energy modeling, with a focus on the Long-range Energy Alternatives Planning (LEAP) system. It explores the structure and features of LEAP, its applications in various countries, and its role in simulating electricity demand and assessing sustainable energy scenarios. Additionally, the review discusses the challenges and limitations of LEAP-based studies and examines the current state of Bangladesh's energy sector, highlighting the need for strategic diversification and the constraints in meeting future electricity demand.

2.2 Overview of LEAP Model

The Long-range Energy Alternatives Planning (LEAP) system, developed by the Stockholm Environment Institute, is a widely used tool for energy policy analysis and climate change mitigation planning [1]. It functions as a bottom-up, scenario-based energy modeling tool, enabling countries and regions to simulate energy demand, supply, costs, and environmental impacts. Unlike optimization models, LEAP uses accounting methods to track energy flows and emissions, making it suitable for long-term policy analysis, including targets extending to 2030 or 2050 [1].

2.3 LEAP Model Structure and Features

LEAP's flexibility is evident in its modular structure, including the Key Assumptions (drivers), Demand, Transformation, and Resource modules. It also incorporates the Technology and Environment Database (TED), offering technical and environmental data for over 1,000 energy technologies [2]. The system supports both short- and long-term energy transition analysis and is frequently used to model the impact of energy policies across various economic sectors.

2.4 Application of LEAP in Country-Level Studies

A variety of country-level and regional studies have successfully applied the LEAP model to simulate electricity demand and assess sustainable energy scenarios. In Colombia, used LEAP to simulate national energy demand and GHG emissions under multiple scenarios through 2050 [3]. The study focused on the electricity sector, examining technological transitions such as the adoption of electric vehicles, clean fuels, and renewable power generation. The analysis revealed that while electricity demand would increase in future scenarios, emissions would significantly decrease under more ambitious sustainability pathways. However, limitations included the assumption of constant energy intensities in some sectors and data constraints.

2.5 Application of LEAP in Regional and Global Contexts

In Andalusia, Spain, [4] employed LEAP to develop baseline, efficiency, and long-term transition scenarios. Their research found that while energy efficiency and increased renewable energy penetration could reduce emissions, these measures were insufficient to meet 2050 climate neutrality goals without significant policy reform and systemic electrification. The study's sector-based demand modeling approach enhances transparency and replicability.

Similarly, In Pakistan, two separate studies demonstrated LEAP’s application [5] projected electricity demand and analyzed five supply-side scenarios (Business-As-Usual, Coal, Gas, Nuclear, and Renewables) from 2016 to 2040. Although the renewable scenario offered the lowest emissions and external costs, the lack of demand-side analysis was a significant limitation. In a more comprehensive approach, [6] forecast electricity demand from 2015 to 2050 and evaluated four scenarios: Reference, Renewable Energy Technologies (RET), Clean Coal Maximum (CCM), and Energy Efficiency & Conservation (EEC). RET proved most sustainable, while EEC was the most cost-effective. However, both REF and CCM scenarios failed to meet long-term sustainability goals.

2.6 LEAP in Emerging and Developing Countries

In Benin, [7] combined LEAP with multi-criteria decision analysis using Fuzzy AHP and TOPSIS to evaluate electricity demand and sustainable development policies. Among three modeled scenarios, the High-Efficiency Energy Application (HEEA) scenario proved most sustainable, significantly reducing GHG emissions. However, the study lacked cost assessment and relied on estimated sectoral data due to local data unavailability.

In Panama, [8] utilized LEAP to analyze the effects of renewable energy legislation (Law 44) through four scenarios from 2013 to 2026. The study revealed that although renewable energy implementation could reduce costs and emissions, the short analysis horizon and lack of grid interconnection modeling were limiting factors.

In Malaysia, [9] developed five LEAP scenarios aligning with the National Energy Transition Roadmap (NETR) and Renewable Energy Roadmap. Results emphasized the critical role of solar PV and energy storage systems in achieving sustainability by 2050. However, the study did not explore the integration of LEAP with optimization models such as NEMO, nor did it deeply analyze storage technologies.

Finally, in Shanghai's Lin-gang Special Area in China, [10] developed Baseline, Low-Carbon, and Enhanced Low-Carbon scenarios extending to 2060. The Enhanced scenario, incorporating electrification and industrial upgrades, achieved emissions peaking by 2030 and near carbon neutrality by 2060. This highlighted the effectiveness of sector-specific transformations and clean energy substitution in urban low-carbon planning.

These case studies demonstrate LEAP's robustness, adaptability, and clarity in modeling diverse electricity systems. While scenario analysis and modular structure enhance its policy relevance, consistent challenges include data limitations, static assumptions, and insufficient incorporation of economic and social dimensions.

2.7 Bangladesh’s Energy Landscape

Bangladesh's electricity sector has undergone significant transformation in recent years, yet still faces substantial challenges. As of recent assessments, electricity access rates in the country have improved dramatically from approximately 49% to between 85-90% of the population, though 10-15% of Bangladeshis still lack electricity access [11]. Despite this improvement, Bangladesh's per capita electricity consumption remains remarkably low at around 321 kWh, which is among the lowest in the world [12].

The country's electricity generation mix is heavily dependent on natural gas, which accounts for 53-62% of the total generation capacity [13] [14]. Other significant contributors include heavy fuel oil (22-30%), imported electricity from India (4.55%), coal (1.9%), and a small portion from renewable sources including hydropower (1.75%) [14] [15]. This heavy reliance on natural gas is concerning as the country's reserves, estimated at 27.12 trillion cubic feet (TCF), have already been depleted by about 15.22 TCF as of 2017, with only 10-15 years of reserves remaining at current consumption rates [13] [14].

2.8 Challenges in Bangladesh’s Energy Sector

The installed electricity generation capacity in Bangladesh has grown substantially, reaching approximately 19,630 MW in 2020, up from 8,535 MW in 2012 [15] [16]. Despite this growth, the country still faces significant challenges in meeting its electricity demand. The peak demand frequently exceeds generation capacity, with Bangladesh needing to import around 1,160 MW of electricity to bridge this gap [16].

With Bangladesh's robust economic growth (GDP growth of 8.13% in 2018/19), electricity demand is projected to increase dramatically [13]. Forecasts suggest that electricity demand will reach 66,804 MW by 2030, creating a substantial gap of 50,309 MW between demand and generation capacity if significant investments are not made [13]. Looking further ahead, the Power System Master Plan (PSMP) aims to increase generation capacity from 22 GW to 60 GW by 2041 [14].

2.9 Strategic Diversification and Sustainability

To address these challenges, Bangladesh is exploring diversification of its energy sources. The government is investigating alternative energy resources such as solar, wind, hydroelectricity, biomass, and biogas to supplement fossil fuels [17]. Additionally, the PSMP has adopted a fuel diversification policy that includes imported coal, liquefied natural gas (LNG), and nuclear fuel [14]. This diversification strategy is crucial for ensuring energy security, supporting industrial development, and meeting Bangladesh's growing electricity demands while reducing dependence on depleting natural gas reserves.

2.10 Economic and Environmental Constraints

Bangladesh's ambitious electricity expansion plans face significant challenges that could undermine the country's energy security and economic stability. Perhaps the most pressing concern is the growing dependency on imported fuels. According to the Power System Master Plan (PSMP) 2016, Bangladesh would need to import 60 million tons of coal annually by 2041, while 70% of gas demand would be supplied from imported LNG [18]. This heavy reliance on foreign energy sources exposes Bangladesh to volatile global fuel markets, a risk already evidenced by the country's experience with petroleum-based rental and quick rental power plants that significantly increased generation costs [19].

2.11 Infrastructure and Technical Challenges

Financial constraints also pose substantial challenges. The levelized cost of electricity from off-grid options is significantly higher than the regulated tariff for grid electricity consumers, making sustainable off-grid solutions economically challenging. While low-income consumers might pay about half the cost of owning a Solar Home System (SHS) for comparable energy use, problems arise when demand restrictions are removed. Higher consumption levels could lead to burdensome monthly bills despite reductions in per-kilowatt-hour costs, due to high capacity-related and operating costs [19].

The rapid depletion of domestic natural gas reserves represents another critical constraint. Bangladesh's natural gas reserves of 27.12 trillion cubic feet (TCF) have already been depleted by about 15.22 TCF as of 2017, with only 10-15 years of reserves remaining at current consumption rates [13] [14]. This resource limitation is particularly concerning given that natural gas currently accounts for 53-62% of the country's electricity generation mix [14].

The gap between electricity demand and generation capacity is expected to widen dramatically in the coming decades. With Bangladesh's high GDP growth rate (8.13% in 2018/19), electricity demand is projected to reach 66,804 MW by 2030, creating a potential gap of 50,309 MW between demand and generation capacity if significant investments are not made [13]. This challenge is compounded by the country's rapidly increasing electricity consumption, which has grown by 120-135% every five years [13].

Environmental sustainability presents another significant constraint. Bangladesh's shift toward coal and LNG may conflict with global decarbonization commitments, creating tension between meeting immediate electricity needs and achieving long-term sustainability goals [18]. While the government is exploring alternative energy resources such as solar, wind, hydroelectricity, biomass, and biogas to supplement fossil fuels [17], the prospects for renewable energy in Bangladesh are considered limited according to current assessments, making the country's future energy security primarily dependent on coal, LNG, and nuclear-based plants [14].

Limited technical capacity and infrastructure constraints further complicate Bangladesh's electricity outlook. The country's transmission and distribution networks require significant upgrades to accommodate increased generation capacity and reduce system losses. Additionally, Bangladesh faces challenges in developing the technical expertise and institutional frameworks necessary for effectively managing complex energy systems, particularly as it incorporates new technologies like nuclear power and large-scale renewable energy projects.

Chapter 3: Description of the model/System

3.1 Introduction

Using the LEAP (Long-range Energy Alternatives Planning) software, we created a long-term forecasting model to find out how Bangladesh's energy consumption would change by 2050. With special emphasis on sector-specific consumption patterns and potential development paths, the model is designed to depict the demand-side structure of Bangladesh's energy system. In order to make sure the system operates properly before making future projections, the model has been tested by comparing simulated results with real data from BPDB and IEA upto 2022 taking base year of 2013.

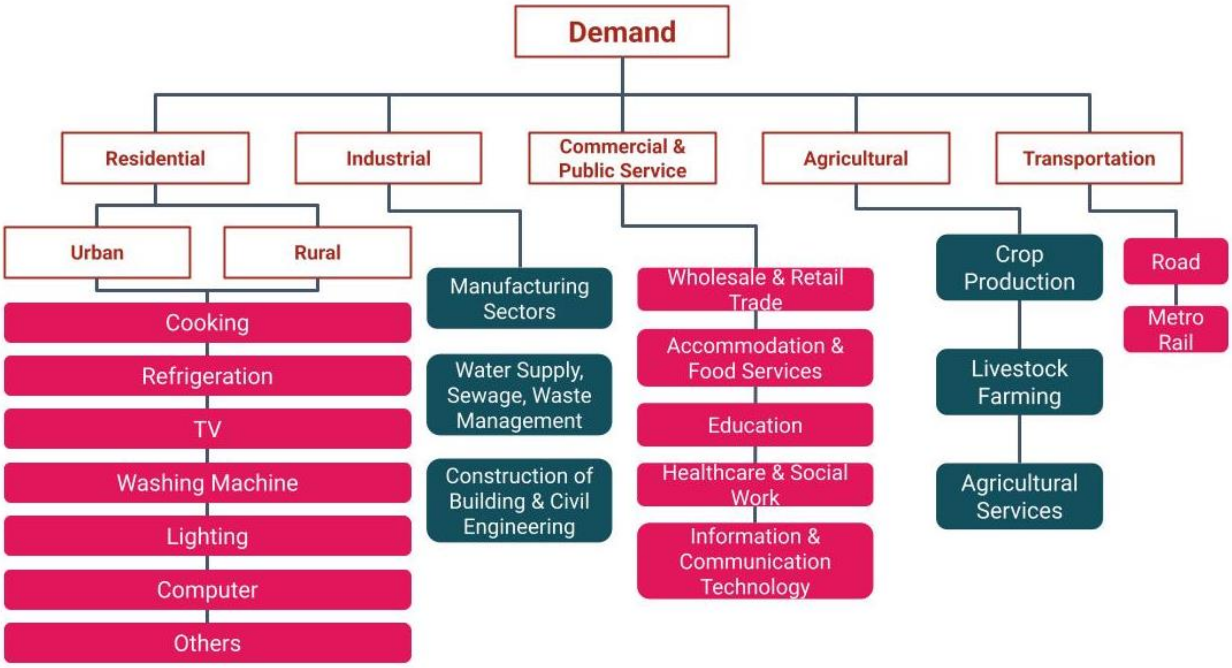

Figure 1 Demand Branches

3.2 Transformation Module

Beyond end-use demand, our model also includes a Transformation module to account for the generation and supply of electricity. This includes the role of power plants and the conversion of primary resources into usable electricity. This module ensures that demand forecasts are matched with appropriate supply assumptions, creating a more holistic view of the energy system.

3.3 Scenario Design

To explore different possible futures, we developed four distinct scenarios:

- Business-as-Usual (BAU): Assumes no major policy or technology shifts; growth continues based on historical patterns. This serves as the baseline for comparison.
- Accelerated Development Scenario (ADS): Represents a high-growth path with rapid electrification, increased economic activity, and widespread use of efficient technologies along with higher rate of industrialization and urbanization. Demand grows significantly but remains optimized.
- Moderate Transition Scenario (MTS): Reflects a more balanced future with moderate policy intervention, partial electrification, and manageable growth in electricity use.
- Low Emission Sustainability Scenario (LESS): Focuses on climate-friendly strategies, including strong energy efficiency measures and increased reliance on renewable resources. This scenario assumes slower but cleaner growth.

Together, these scenarios allow for a comprehensive understanding of how different development paths could affect electricity demand and emissions across Bangladesh's key sectors.

Chapter 4: Methodology

4.1 Introduction

This chapter outlines the methodology used to develop and validate a long-term energy forecasting model for Bangladesh using the LEAP (Long-range Energy Alternatives Planning) software. It details the process of creating a demand-side model based on sector-specific data, followed by scenario formulation to project future electricity demand and supply. The methodology also includes data collection, model validation, scenario parameterization, and sensitivity analysis, which ensures the robustness and reliability of the model's projections.

4.2 Workflow

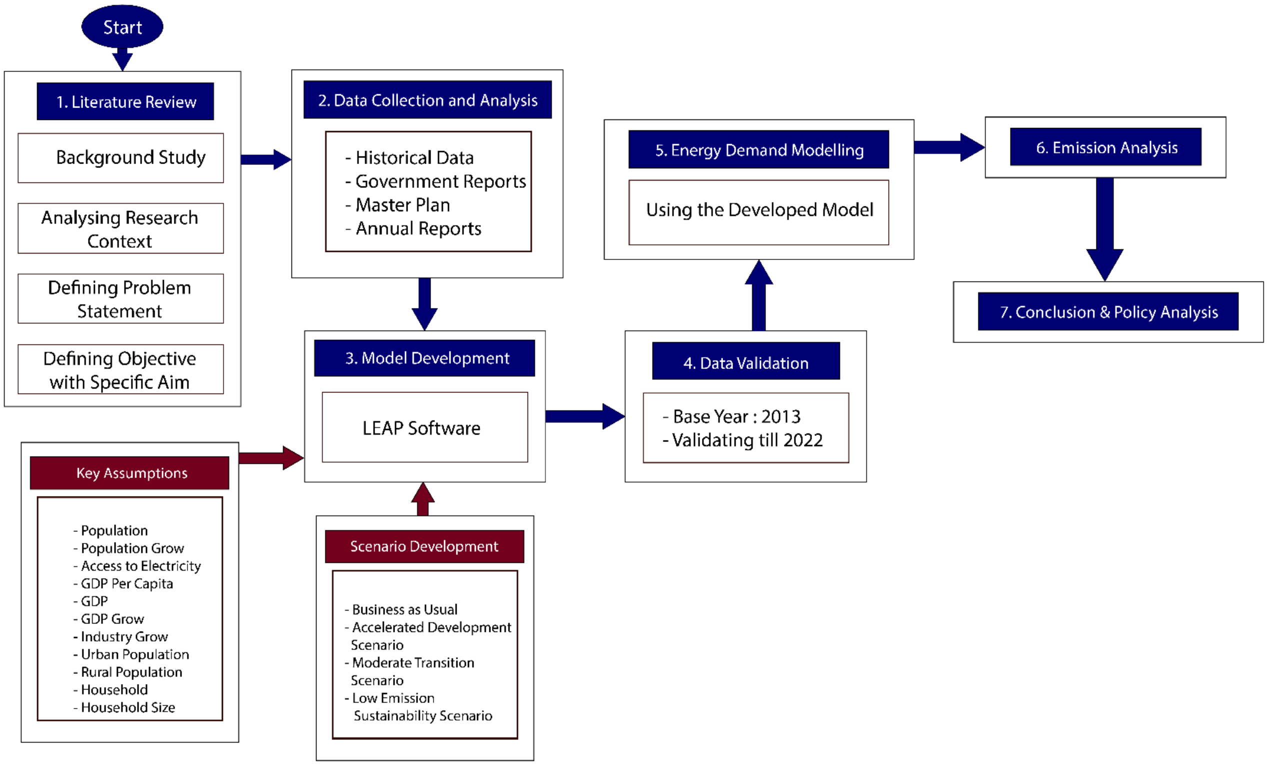

Figure 2 Workflow Diagram

From figure 2, it is clear that the modeling procedure begins with a thorough literature analysis to find existing research on long-term electricity forecasts, appropriate modeling approaches, and significant sectoral drivers in energy systems. Following that, we collected historical and projected data on population, electrification rates, GDP growth, sector-specific activity, and power consumption patterns.

The Model Development phase is where we created a detailed demand-side framework in LEAP. This includes establishing activity levels and energy intensities for various sectors such as residential, industrial, commercial and public services, agriculture, and transportation. Each sector was further classified according to specific use cases; for example, the Residential sector comprises equipment such as televisions, kitchen units, refrigerators, and more.

We planned on working with four distinct future scenarios: Business as Usual, Accelerated Development, Moderate Transition, and Low Emission Sustainability, each with its own set of assumptions about economic development, technological adoption, efficiency, and electrification.

4.3 Data Collection

Our data came from a combination of national and international sources. These included reports from the Bangladesh Power Development Board (BPDB), the Ministry of Finance, and other publicly available datasets such as Worldometer and IEA data. The data gathered covered a wide range of factors, including sectoral electricity consumption, population growth, the rural-urban divide, technological penetration, and various economic indicators.

To provide consistency and clarity, all input variables were mapped to LEAP-compatible units and periods. When data was lacking or inconsistent, interpolation and logical assumptions were made based on trends from similar industries or nations. [20] [21] [22] [23] [24].

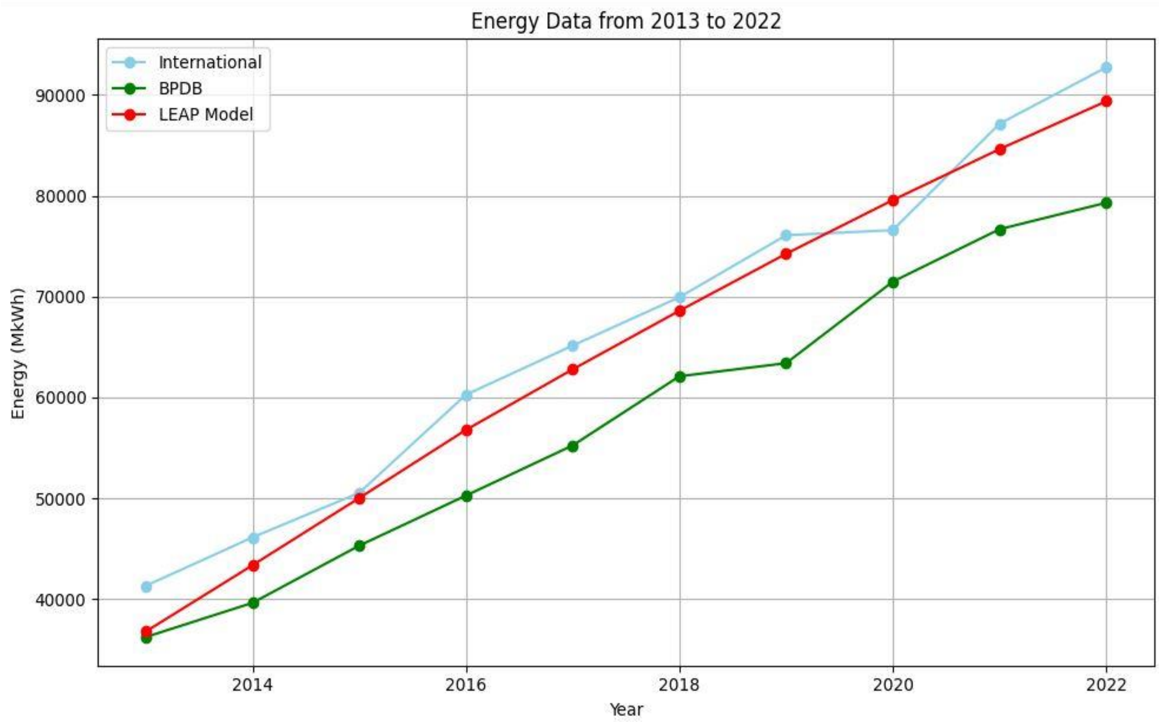

Figure 3 Data Validation Curve

From the figure 3, it is clear that our simulated result lies in between the data provided by BPDB and IEA. As the data for the years except 2013, 2016, 2019 and 2022 were generated by LEAP accurately, it depicts our model's validity.

4.4 Model Validation

Validation is an essential component of every modeling project. In our example, the LEAP model was validated by comparing predicted results for the years from 2013 to 2022 to actual national electricity consumption and sectoral statistics. We gave input data for years 2013, 2016, 2019 and 2022 and the years in between was generated by our LEAP model. The model's output closely matched the real-world data from 2022, confirming the validity of our assumptions and structure.

This validation not only increased trust in the model's reliability, but also acted as a checkpoint prior to moving forward with long-term scenario forecasting.

4.5 Scenario Formulation and Parameterization

We established four post-2022 pathways - BAU, ADS, MTS, and LESS by only modifying the drivers and levers that policy can really affect. We defined the following for each scenario:

- **Macro drivers:** the total population, the percentage of people living in cities, the growth of GDP and value-added in different sectors, the number of households, and access to electricity.
- **Demand levers :** Sector activity (like homes, floor area, and industrial output indices), useable energy intensities by end use (like TVs, refrigerators, motors, lighting, cooking, and ICT), and device efficiency.
- **Electrification shares:** ways that end-uses can switch from fossil fuels to electricity.
- **Transport electrification:** electricity demand for EVs and metros (as activity × intensity), kept outside of the system to minimize feedback loops.

We input all of the time courses as LEAP expressions utilizing fixed points (2013, 2016, 2019, 2022) and future values that were interpolated (for example, Interp(year, value, …) or compound growth Growth(x%)).

4.6 Demand Module Construction

We organized end-use electricity demand in LEAP by sector and then populated a small number of practical drivers for each sector. LEAP handled the internal calculations; our task was to set realistic activity levels and technology paths, and to keep 2013–2022 aligned with history.

- **Residential :** There are separate urban and rural branches. Activity was the number of households (from population, household size, and urbanization). For each appliance/end-use (lighting, refrigeration, TV/ICT, fans/AC, cooking, etc.) we specified appliance ownership/saturation paths and efficiency improvements by scenario. This allowed BAU to follow observed trends while ADS and MTS accelerated efficiency and electrification (e.g., higher induction/electric cooking uptake).
- **Industry :** There are three sub-sectors. All Manufacturing**,** Water & Waste**,** Construction were represented with production proxies consistent with GDP/sector value added. We set useful-energy intensity trajectories at the sub-sector level and applied scenario-specific efficiency gains (faster motor-system upgrades and process optimization in ADS/MTS; gradual improvements in BAU).
- **Commercial & Public Services :** Demand was driven by a service activity proxy (growth in service value added and floor space). End-uses include lighting, HVAC, office equipment/ICT and other plug loads. Efficiency assumptions vary by scenario (e.g., faster LED and high-efficiency HVAC penetration in ADS/MTS).
- **Agriculture :** Electricity use for irrigation pumping, processing and services was linked to crop/livestock activity indicators. Efficiency improvements (pump upgrades, VFDs) were stronger in ADS/MTS.
- **Transport (electric) :** Two components were modeled explicitly:
    1. **Electric vehicles (EVs)**—fleet growth and average annual electricity use;
    2. **Metro rail**—treated as a separate electricity branch with exogenous totals by scenario timeline.

BAU keeps EV/metro contributions modest; ADS ramps both; MTS grows steadily but within feasibility limits; LESS prioritizes efficiency over absolute growth.

Across all sectors, 2013–2022 inputs were calibrated so that LEAP reproduces historical totals. Post-2022, each scenario diverges only through these **drivers** (activity growth, electrification shares, technology efficiency and ownership), not through any manual manipulation of results.

4.7 Transformation Module Configuration

The supply side represents how primary fuels are converted to electricity in Bangladesh. We included the major thermal process families used in the grid:

- **Combined Cycle Gas Turbine (CCGT)** – main baseload/shoulder generator.
- **Steam Turbine (ST)** – legacy steam plants (gas/coal/liquid) with declining relative role.
- **Oil-Fired Turbine/Engine (OIL)** – peaking and backup service.
- **Non-thermal placeholders** (Hydro, Solar PV, Nuclear, Others) were kept to represent non-fossil additions indirectly by reducing thermal dispatch requirements.

For each process we specified: exogenous capacity (where applicable), simple merit-order/dispatch rules consistent with Bangladesh's grid, and typical efficiencies. Scenario differentiation occurs through run-hours implied by demand and through modest efficiency improvements were justified (e.g., better CCGT heat rates in ADS/MTS).

4.8 Environmental Effects (Emissions) Configuration

The LEAP emissions module was configured to track four combustion-related pollutants for all electricity-generation processes (steam turbine, oil-fired turbine/engine, and combined-cycle gas turbine): carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), and nitrogen oxides (NO_x). For each process, average environmental loading factors were specified in mass per unit energy (kg/TJ of final energy consumed). CO_2 factors reflect fuel carbon content and oxidation; CO and CH_4 capture incomplete combustion; NO_x reflects typical burner and flame-temperature conditions. Factors were entered in Current Accounts and kept consistent across scenarios unless a process-specific control or efficiency improvement required adjustment. Emissions are reported in Environmental Effects (Emissions) as annual totals (thousand tonnes/year) disaggregated by process and fuel, enabling direct scenario comparison.

4.9 Data Harmonization and Unit Handling

All inputs were converted to LEAP-compatible units and consistent time bases (e.g., people → households, GDP/value-added indices, electricity in GWh/TJ). When sources differed, we reconciled to national statistics and used interpolation for missing years. Post-calibration checks confirmed that base-year sector totals equal national consumption and that the sum of end-uses equals branch totals.

4.10 Sensitivity Analysis and Uncertainty Handling

To understand how robust our conclusions are to input uncertainty, we conducted a targeted sensitivity analysis focused on the model drivers most likely to change in practice.

4.10.1 Choice of parameters tested

Based on expert judgment and literature, we selected three high-impact inputs:

- GDP/sector growth rate (affects activity levels),

- Electrification/adoption rate for key end-uses (e.g., EV penetration, electric cooking),
- Efficiency improvement rates (useful energy intensity reductions).

4.10.2 Perturbation method. Each parameter was varied individually while keeping others fixed:

- GDP/sector growth: ±10% from baseline growth paths,
- Electrification shares: ±2–5 percentage points depending on end-use plausibility,
- Efficiency improvements: ±5 percentage points in cumulative intensity reduction by 2050.

4.10.3 Observed effects. Changes produced proportional and intuitive responses in electricity demand and emissions:

- GDP sensitivity produced the largest absolute impact on 2050 demand (demand scales with economic activity),
- Electrification shifts changed the fuel mix but had a smaller immediate effect on total final energy than GDP,
- Efficiency improvements reduced peak and cumulative demand, highlighting the leverage of end-use measures.

4.10.4 Interpretation and use. The sensitivity runs quantify uncertainty bands around our central scenario results and identify which levers most affect outcomes. This guided our policy recommendations: prioritize measures (e.g., efficiency and targeted electrification) that produce the largest demand or emissions reductions per unit of policy effort.

4.10.5 Limitations. The sensitivity analysis is not exhaustive (we did not vary every parameter simultaneously or run probabilistic sampling). Instead, it provides a focused assessment that supports the robustness of the scenario comparisons and helps indicate where further, deeper uncertainty analysis would be most valuable.

Chapter 5: Results and Discussions

5.1 Introduction

The LEAP outputs for four post-2022 pathways i.e. Business-as-Usual (BAU), Accelerated Development Scenario (ADS), Low-Emission Sustainability Scenario (LESS), and Moderate Transition Scenario (MTS) are synthesized in this chapter. The macro-assumptions (population, GDP, urban/rural split) are consistent through 2022 and diverge thereafter. The results are described in two phases:

a) Projected demand trajectory (Refer to: Energy Demand Trend).

   This depicts how the total demand for electricity changes over time until 2050 for each policy/technology package.

b) Supply reaction (Data: BAU, ADS, LESS, MTS). The stacked bars illustrate how much power each thermal technology family i.e. Combined Cycle, Oil Turbine, and Steam Turbine can generate. These are the main sources of dispatchable supply in the model. Non-thermal additions are implicitly indicated by decreased thermal run-hours.

Interpretation emphasizes chronology (peak years), direction (growth versus decline), and relative shares, which remain consistent regardless of unit selections.

5.2 National electricity demand outlook (2022–2050)

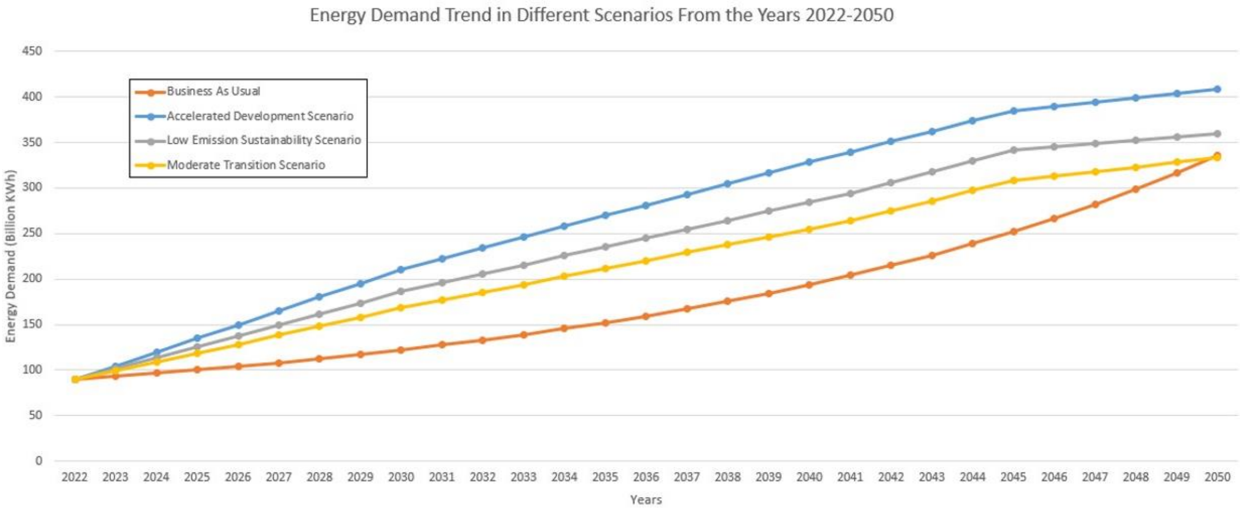

Figure 4 Electricity Demand Outlook (2022-2050)

A comparison is shown in figure 4 where all scenarios show steady growth in demand, which is caused by growing populations, urbanization, industrial activity, and the spread of appliances. The difference between possibilities is how strong electrification is and how efficiency can make up for it.

BAU grows slowly but steadily. It stays at the low end of total demand by 2050 because it thinks that projects will be completed and policies will change slowly.

ADS anticipates that industry, buildings, and transportation will quickly become more industrialized and electrified. Demand grows the fastest and stays the highest until 2050.

LESS shows that there are high demands for efficiency and cleaner technologies. Demand tracks between BAU and ADS. It is lower than ADS because of efficiency gains, but it is greater than BAU because electrification is still growing.

After 2035, MTS is clearly set between BAU and LESS. It assumes realistic efficiency/DSM uptake and moderate electrification, which makes for a mid-range demand profile that Bangladesh can more easily meet.

Demand uncertainty is material: planning only for the BAU envelope risks under-preparing the system, while targeting ADS without institutional readiness risks stranded assets or shortfalls. The **MTS demand band** offers a prudent planning centerline.

5.3 Supply Mix by Scenario (Transformation Module)

In the 2020s and early 2030s, the system's workhorse remains the Combined Cycle (CCGT) across scenarios, with Oil Turbines/Reciprocating Engines providing peaking/backup and Steam Turbines playing a minor, declining role. The transition pathways are distinguished by the rapidity and magnitude of thermal reduction following the peak.

5.3.1 Business As Usual (BAU)

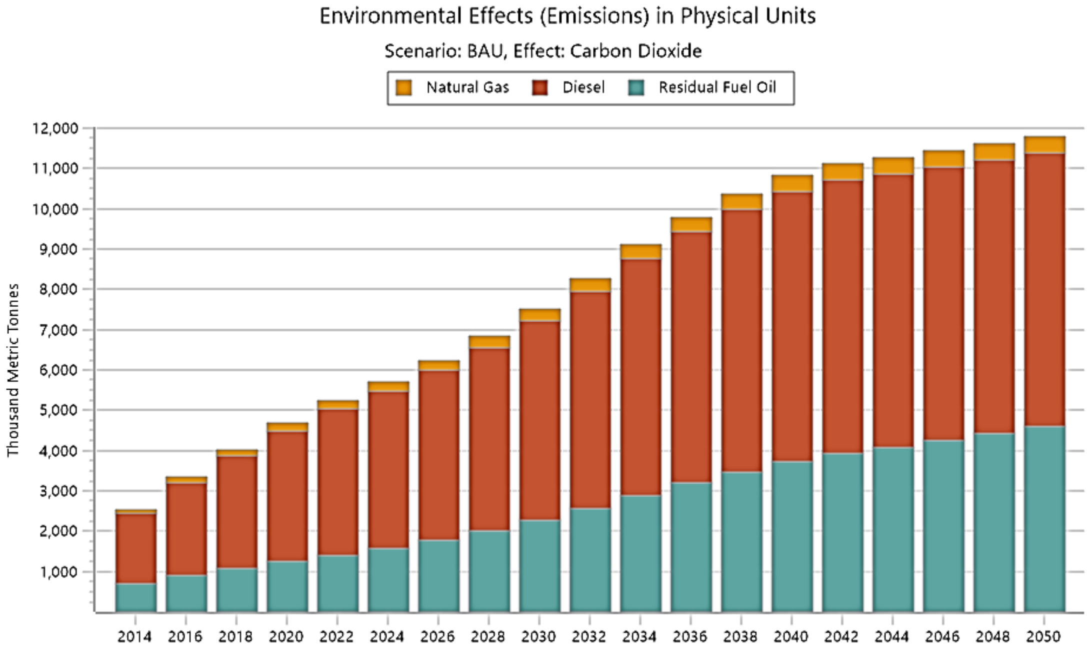

Figure 5 CO_2 Emission Record (BAU)

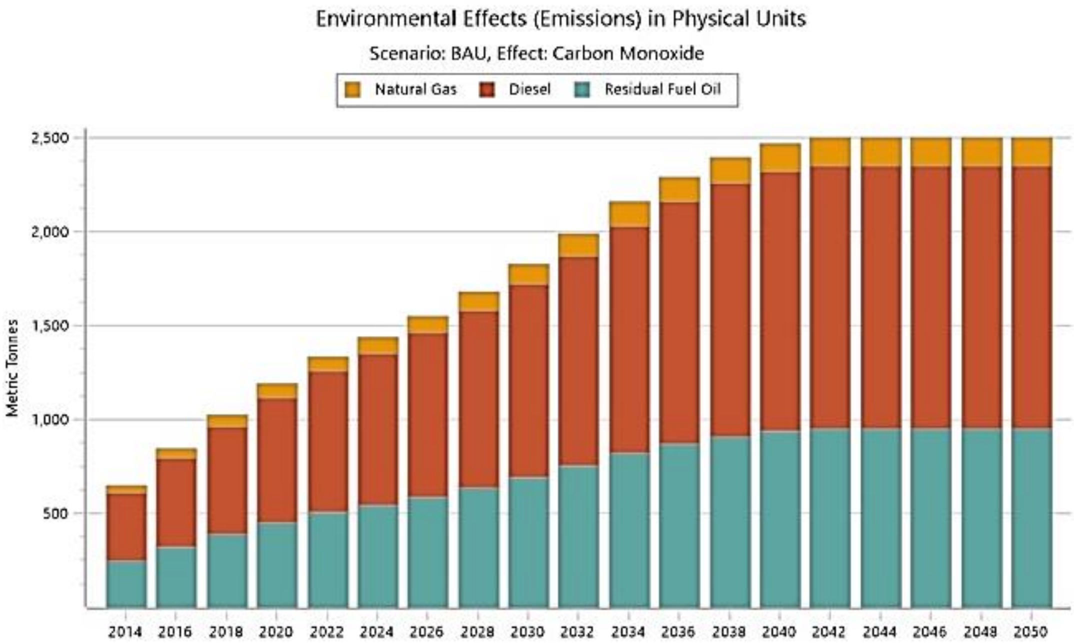

Figure 6 CO Emission Record (BAU)

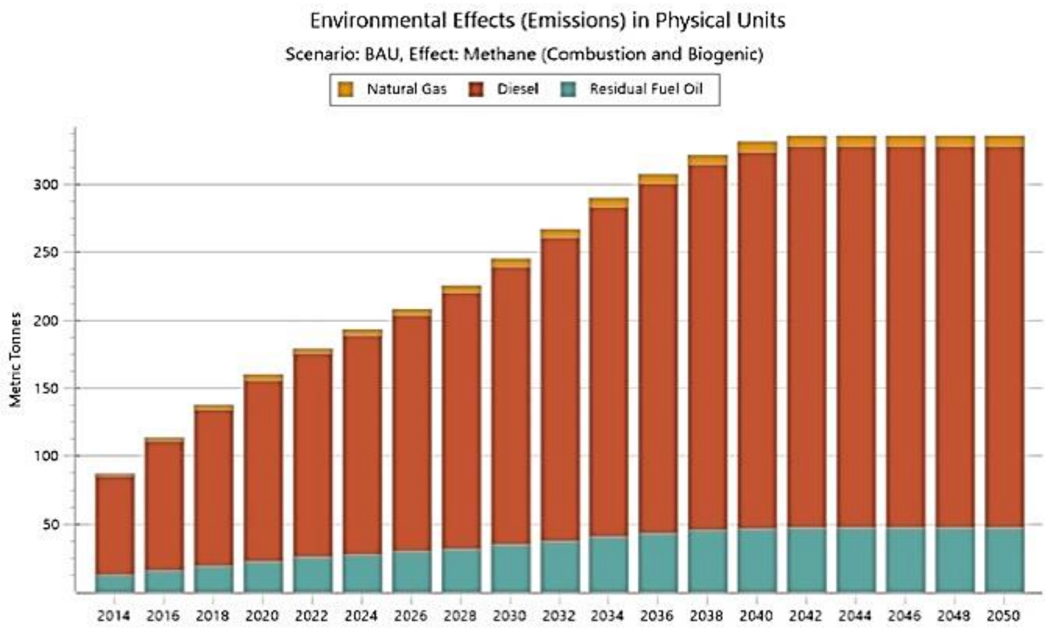

Figure 7 CH_4 Emission Record (BAU)

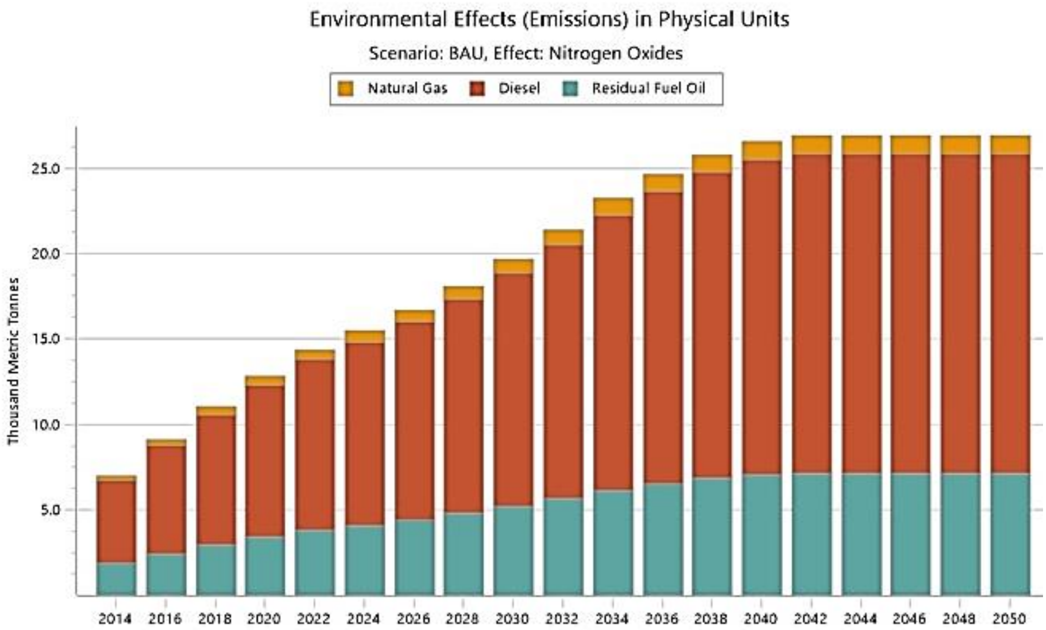

Figure 8 NO_x Emission Record (BAU)

Under BAU, Figure 5 (CO_2) shows a near-monotonic rise from 2013 to the mid–late 2030s, after which the series flattens into a broad plateau through 2050. The height of the stack is governed by combined-cycle gas turbines, with smaller slices from steam turbines and a thin, persistent contribution from oil turbines. The gentle slowdown after 2040 reflects efficiency improvements and demand saturation, but the absolute level does not decline because fossil generation remains dominant in the merit order.

Figure 6 (CO), Figure 7 (CH_4), and Figure 8 (NO_x) display a similar temporal shape: steady growth to the 2030s followed by stabilization. Across these three pollutants the composition is fuel-driven rather than technology-driven. Diesel provides the largest share throughout the horizon, residual fuel oil adds a visible but smaller wedge, and natural gas forms the lowest layer due to lower combustion emission factors and better controls. The leveling after 2040 indicates that even as electricity demand growth slows, continued dispatch of diesel and oil units for peaking and backup keeps CO, CH_4, and NO_x from falling.

Comparing across figures clarifies the levers for mitigation. Figure 5 demonstrates that CO_2 is controlled by the overall generation mix and the dominance of CCGT energy, whereas Figures 6–8 reveal that local-air pollutants are disproportionately influenced by the relatively small fraction of diesel and residual-oil generation. Under BAU, incremental efficiency gains alone are not enough to bend any curve downward. Achieving material reductions would require fuel substitution away from diesel and oil in peaking service and earlier deployment of low- and zero-carbon capacity so that both the CCGT energy share and total fossil output decline rather than merely plateau.

5.3.2 Accelerated Development Scenario (ADS)

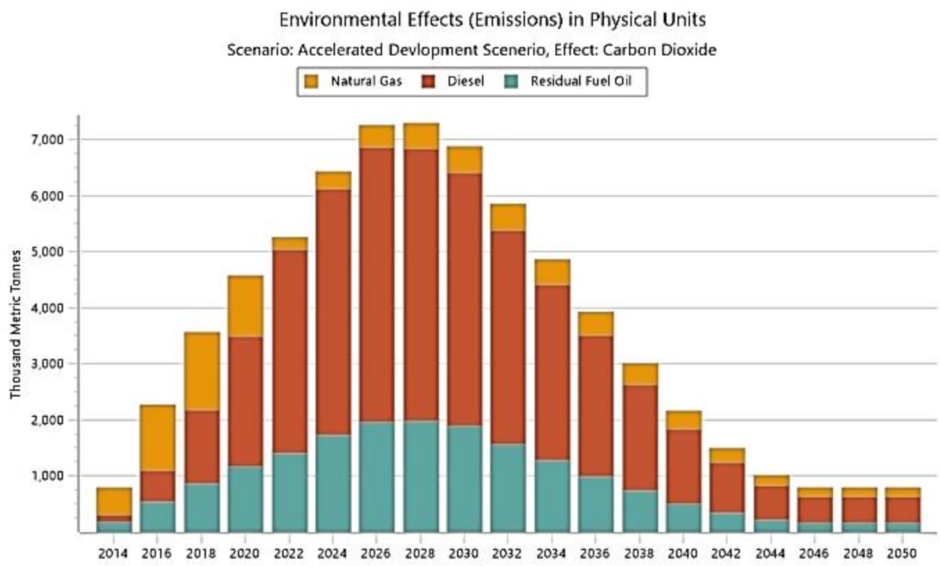

Figure 9 CO_2 Emission (ADS)

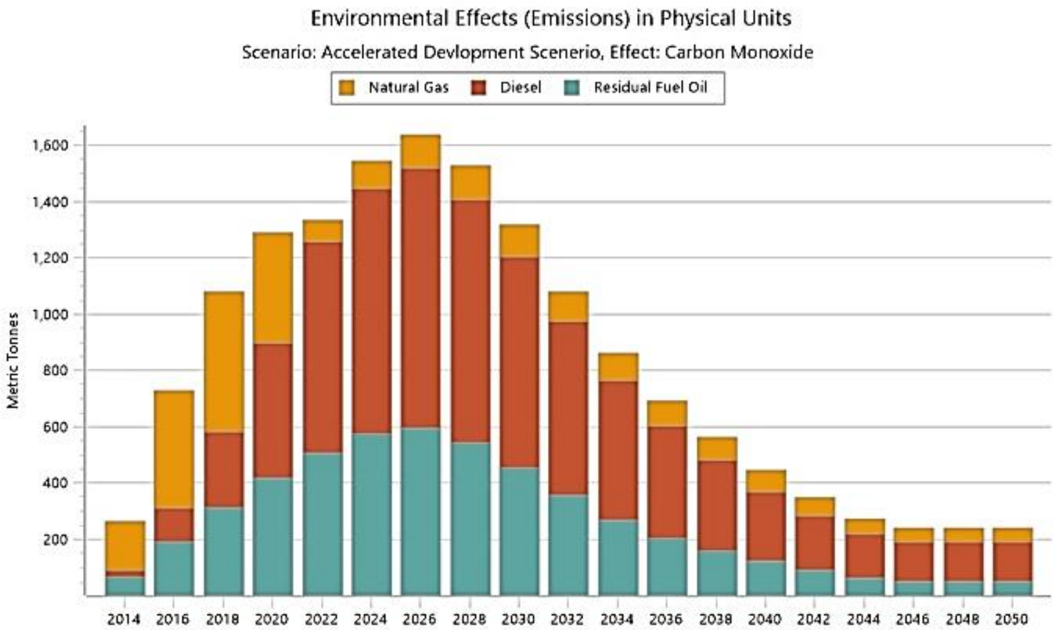

Figure 10 CO Emission (ADS)

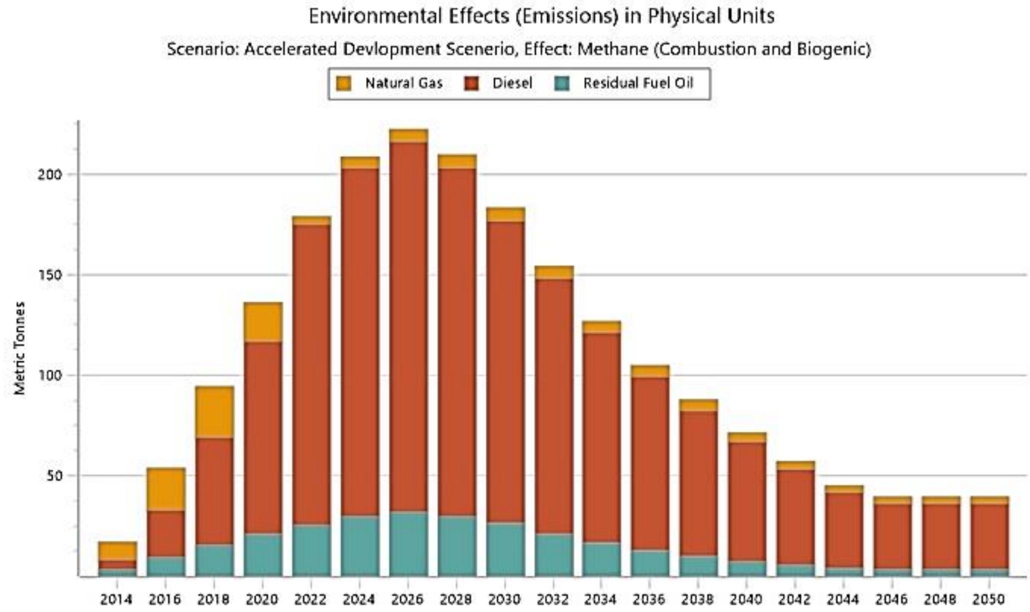

Figure 11 CH_4 Emission (ADS)

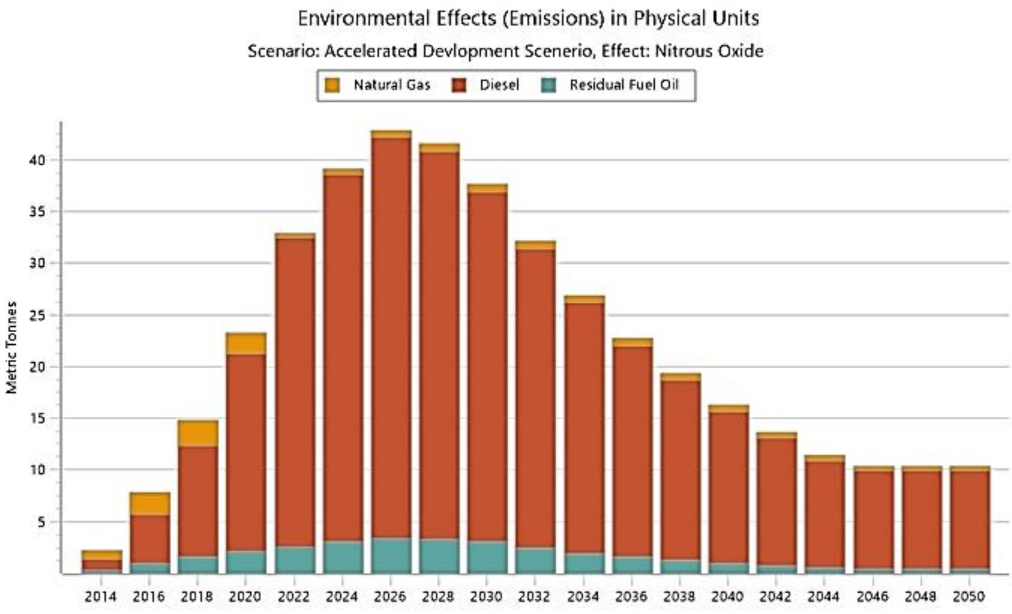

Figure 12 NO_x Emission (ADS)

Under the Accelerated Development Scenario (ADS), all four series show a clear “rise–peak–decline” pattern. Figure 9 (CO_2) climbs rapidly through the 2020s as demand and thermal additions scale up, reaches a distinct system peak in the late-2020s, and then falls sharply from the early-to-mid 2030s, stabilizing on a low plateau after ~2045 as newer, more efficient plants dominate dispatch and legacy oil/diesel units retreat. Figure 10 (CO) follows the same timing at a much smaller magnitude, while Figure 12 (NO_x) traces a parallel arc that moderates as controls improve and oil/steam hours diminish. Figure 11 (CH_4) is the smallest of the four; it rises with expanded gas throughput early on, then drops fastest once gas-system practices (leak mitigation and handling) improve in the 2030s.

Fuel contributions are consistent across Figures 9–12. During the run-up to the peak, diesel and residual fuel oil form visible wedges; these shrink rapidly after 2030 as those units are displaced. Natural gas becomes the mid-period workhorse—temporarily lifting CO_2 in Figure 9 but delivering lower CO and NO_x per kWh in Figures 10 and 12 relative to oil/steam. As combined-cycle replaces older steam and emissions controls tighten, CO and NO_x fall faster than CO_2. For CH_4 (Figure 11), the early increase simply mirrors the larger gas role; the subsequent sharp decline points to effective leak-abatement and improved gas handling.

Overall, Figures 9–12 portray a front-loaded expansion followed by structural decarbonization. Rapid electrification pushes emissions up, but efficiency gains, cleaner dispatch (more CCGT, less oil/diesel), and operational controls drive them decisively down. By the 2040s the system settles into a low-emission steady state: CO_2 remains the dominant residual in Figure 9, while Figures 10–12 show NO_x and CO much reduced and CH_4 minimized—consistent with accelerated development that is consolidated by technology upgrades and fuel switching.

5.3.3 Low Emission Sustainability Scenario (LESS)

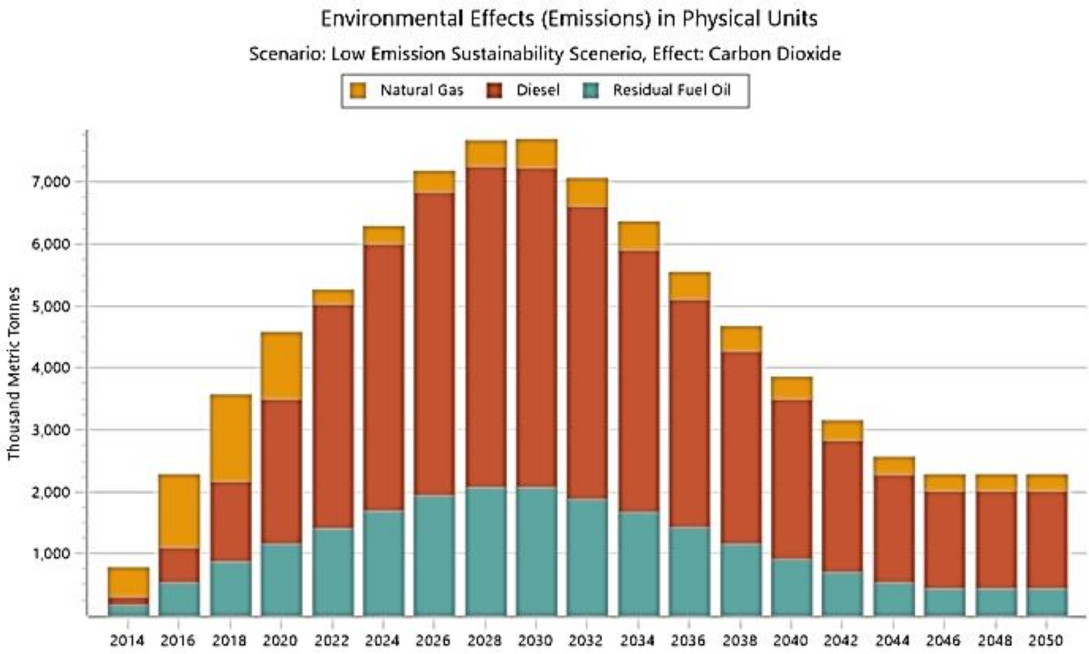

Figure 13 CO_2 Emission (LESS)

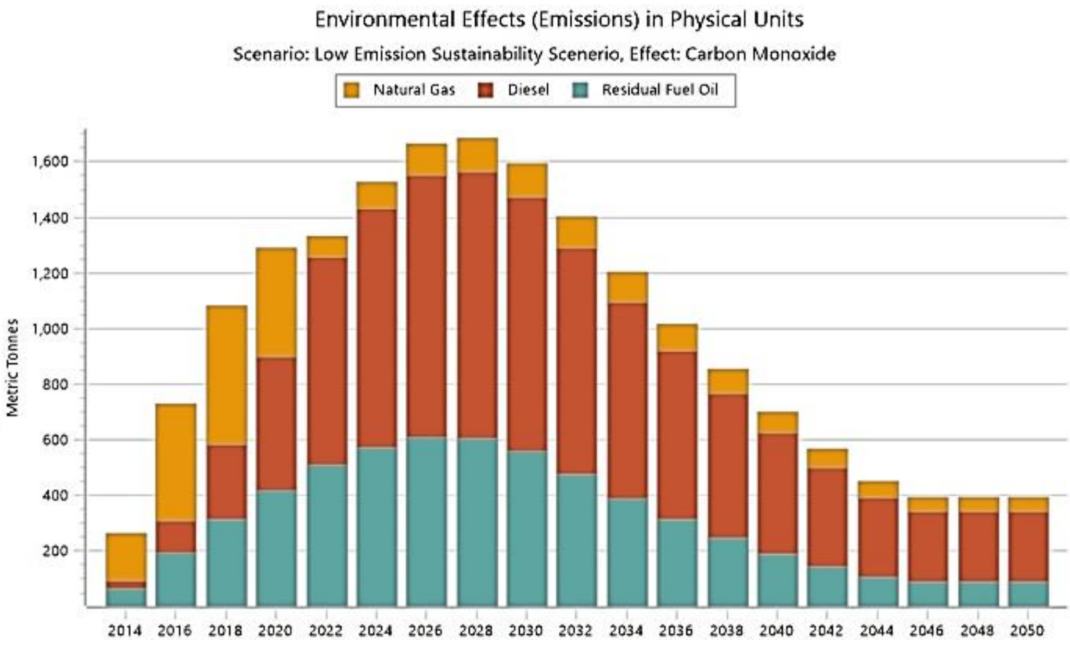

Figure 14 CO Emission (LESS)

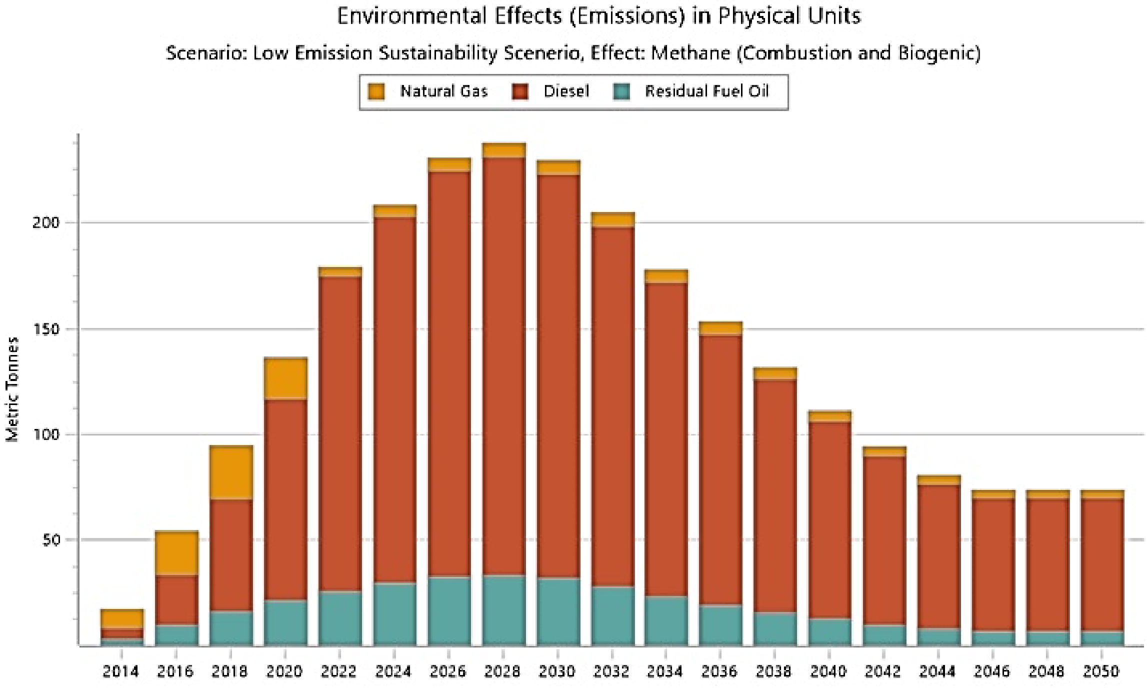

Figure 15 CH_4 Emission (LESS)

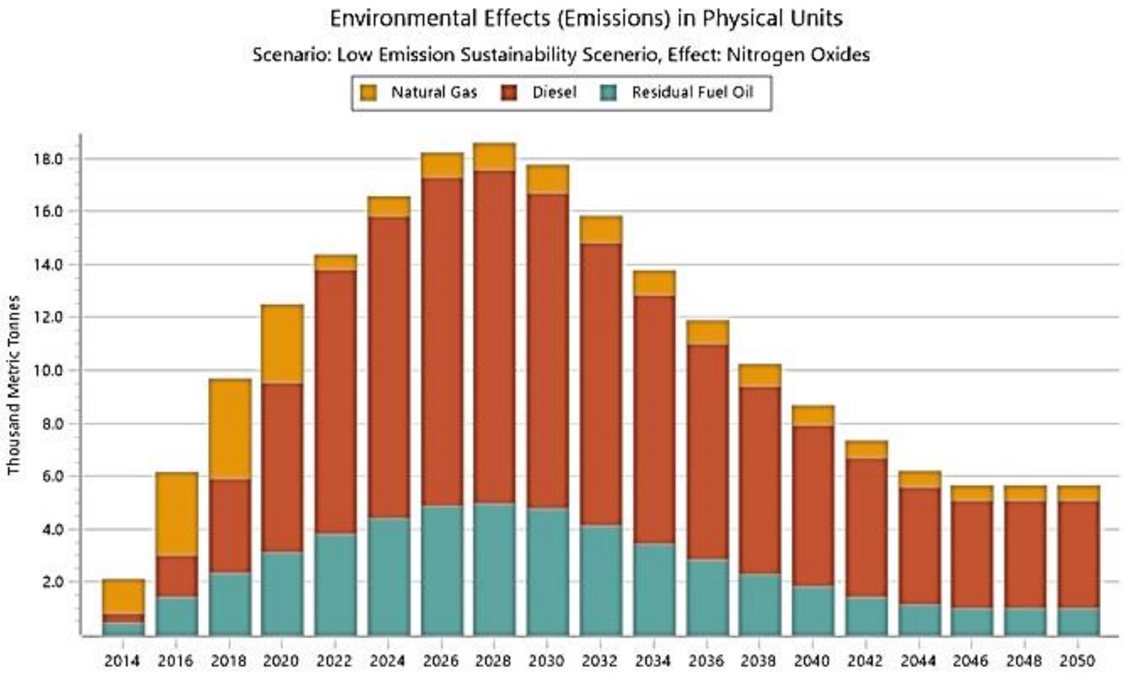

Figure 16 NO_x Emission (LESS)

Under the Low Emission Sustainability Scenario the four panels share the same time profile: emissions climb into the late 2020s, crest around 2027–2029, and then decline steadily to a low, stable plateau by the mid-2040s. In the stacked bars across Figures 13–16 the mid-period height is carried mainly by combined-cycle gas generation, while the diesel and residual-fuel-oil wedges contract quickly after 2030 as those units are displaced and relegated to rare peaking service. This reflects a system that substitutes cleaner supply and captures efficiency gains rather than relying on abrupt shutdowns.

Figure 13 shows carbon dioxide, the largest of the four. CO_2 rises as gas capacity is built and run hard through the 2020s, then falls as demand growth is increasingly met by non-fossil additions, as inefficient steam units retire, and as combined-cycle plants deliver more electricity per unit of fuel. By 2050 the CO_2 stack sits well below its late-2020s peak, indicating that the LESS package of demand-side efficiency and supply diversification produces a structural reduction, not a temporary dip. Figure 14 traces carbon monoxide. CO decreases faster than CO_2 because it is driven disproportionately by oil-based peakers operating at partial load. As those units lose dispatch after 2030 the CO layer contracts rapidly and settles at a low level by the mid-2040s.

Figures 15 and 16 document the gas-linked pollutants. In Figure 15 methane rises while gas throughput expands, then recedes as the generation mix shifts from steam to combined cycle and as leak mitigation and better gas-handling practices are assumed to take hold. In Figure 16 nitrogen oxides follow the same arc but settle a little higher than CH_4 because a small set of thermal units remains online for flexibility needs even in the 2040s and because NO_x outcomes depend on operating hours and control performance, not only on fuel switching. The fuel-based stacks in all four figures confirm the mechanism: after 2030 the diesel band shrinks markedly, the residual-fuel-oil band becomes almost negligible, and most remaining emissions come from combined-cycle gas with improved yet non-zero factors.

Taken together, Figures 13–16 show that LESS achieves substantial and durable reductions without assuming unrealistic retirements. CO_2 falls the most in absolute terms, CO collapses quickly with the phase-down of oil peakers, and CH_4 and NO_x decline more gradually in line with lower gas generation and tighter performance standards. The pattern is consistent with a system that prudently retains some firm thermal capacity for reliability while letting efficiency improvements and non-fossil supply do most of the decarbonization work.

5.3.4 Moderate Transition Scenario (MTS)

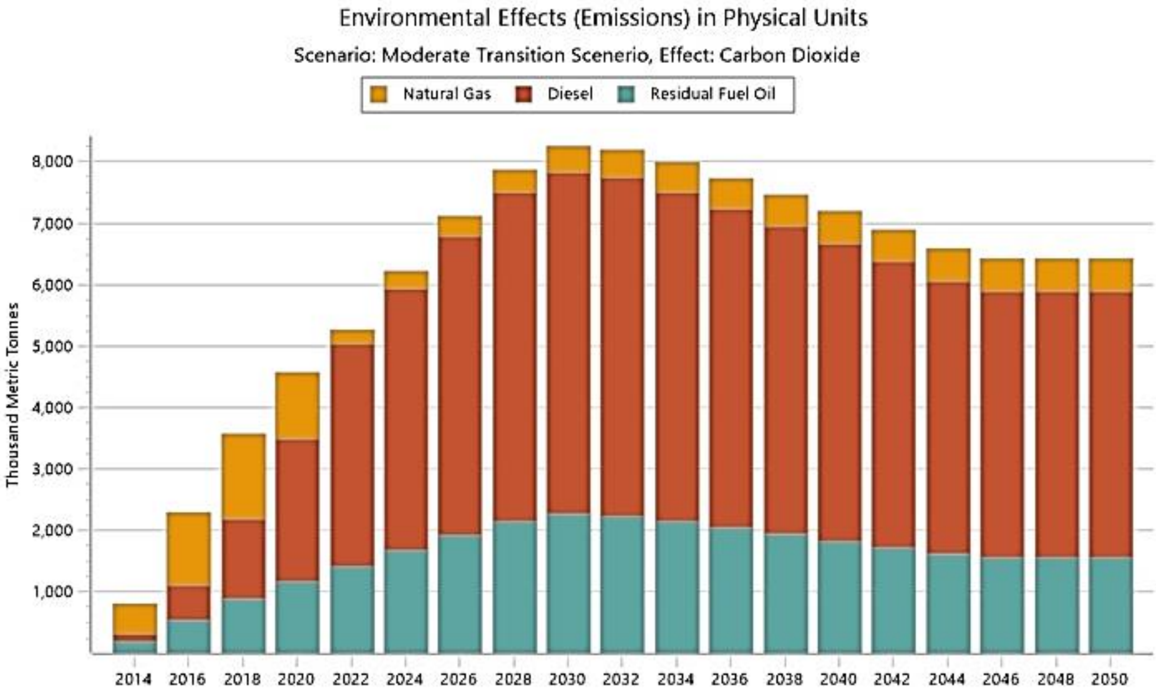

Figure 17 CO_2 Emission (MTS)

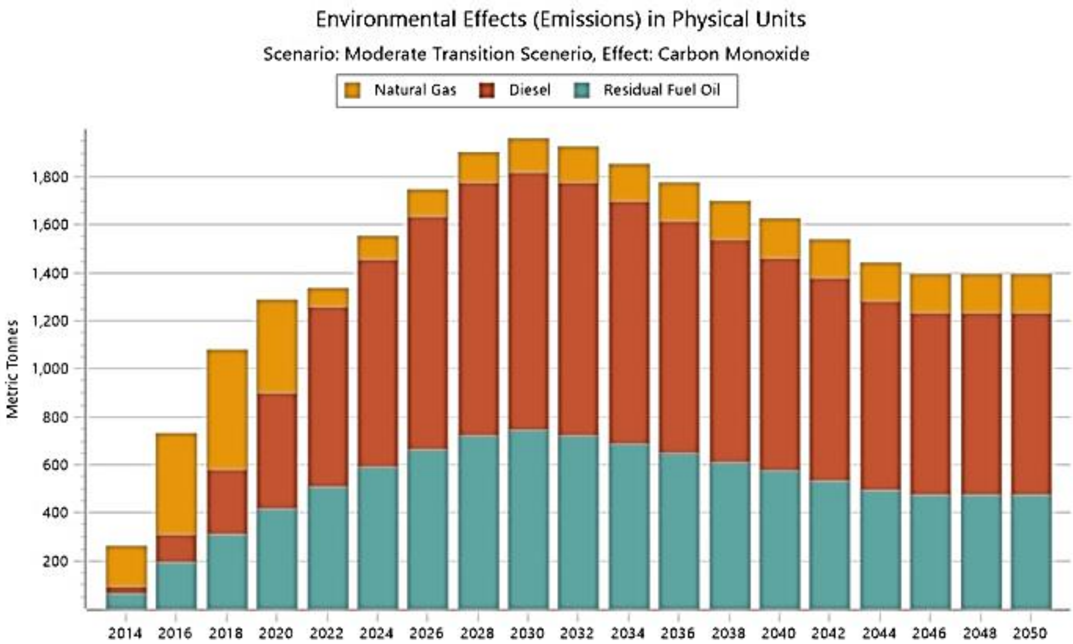

Figure 18 CO Emission (MTS)

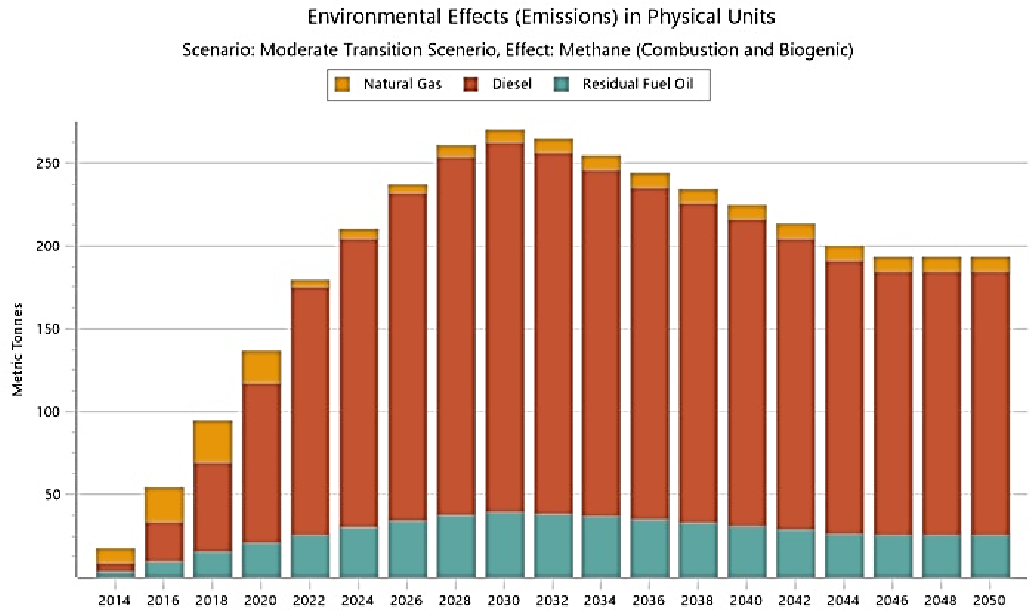

Figure 19 CH_4 Emission (MTS)

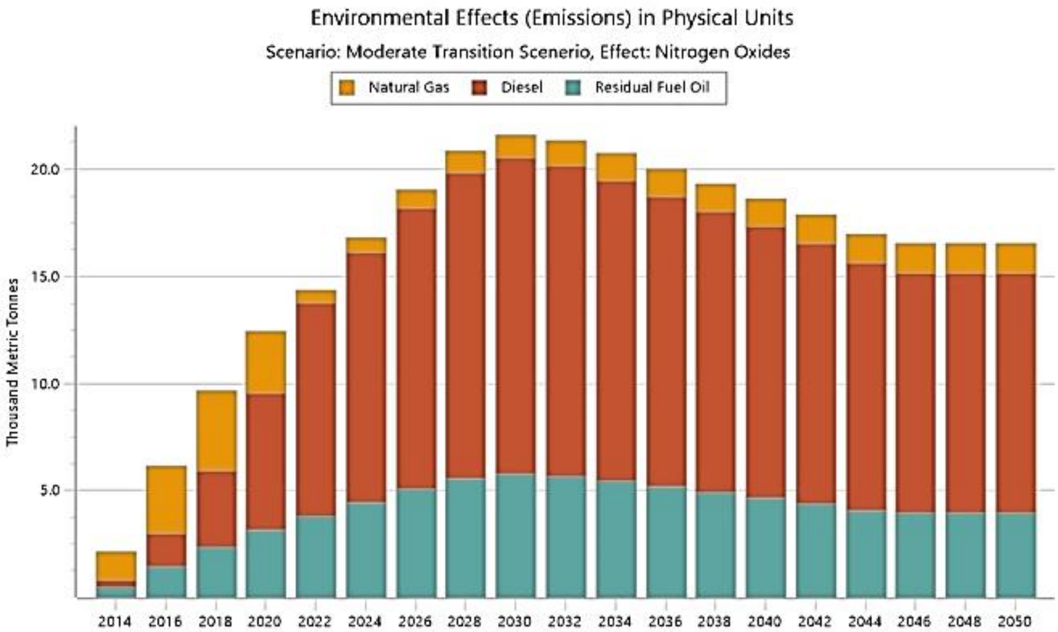

Figure 20 NO_x Emission (MTS)

The Moderate Transition Scenario traces a middle path between BAU's persistent rise and the sharper declines in ADS and LESS. Across the four pollutant charts the system reaches a broad crest around 2029–2032 and then trends downward to 2050 without the deep troughs seen in the more aggressive pathways. In Figure 17 (CO_2) the stacked bars enlarge steadily from 2013 to about 2030 as demand rises and fossil output grows, then flatten and gradually recede as higher-efficiency combined-cycle gas turbines (CCGT) take share and oil-steam units are used less frequently. Figure 18 (CO) echoes the same timing but shows a visibly lower magnitude, reflecting the stronger sensitivity of CO to partial-load operation and to the retreat of diesel and residual-fuel peakers after the early 2030s. Figure 19 (CH_4) rises with the expansion of gas use into the late 2020s, then eases back as the fleet shifts from steam to CCGT and as gas-supply losses are better managed. Figure 20 (NO_x) follows CO's arc, peaking when oil and diesel run hardest in the 2020s and then declining as dispatch shifts toward CCGT equipped with better controls.

Fuel and technology roles are consistent across the panels. In Figure 17 the largest contributor to CO_2 is natural-gas CCGT energy, with a smaller layer from steam turbines and a thin but persistent wedge from oil turbines; efficiency gains in CCGT slow the growth after ~2030 and produce the gentle decline into the 2040s. In Figure 18 diesel dominates CO in the ramp-up years, residual fuel oil adds a visible band, and natural gas forms the lowest layer; once peakers' hours are curtailed, CO falls faster than CO_2. Figure 19 shows that CH_4 is almost entirely a gas story: the early climb tracks higher gas throughput, while the post-2030 decline reflects improved maintenance and lower loss factors as CCGT replaces steam. In Figure 20 diesel again drives the upper portion of the stack through the late 2020s; as those units are displaced by CCGT, NO_x drops in a smooth step-down rather than an abrupt collapse because MTS retains a small oil slice for flexibility.

Reading the four figures together clarifies why MTS flattens rather than crashes. Figure 17 confirms that CO_2 remains the dominant residual because CCGT supplies most electricity even in 2050, albeit at lower intensity than steam or oil. Figures 18 and 20 show a stronger technology signature: both CO and NO_x are highest when oil and diesel are most active and then ease to a visible "floor" after ~2040 as those units are curtailed rather than eliminated. Figure 19 demonstrates that CH_4 behaves like a moderated mirror of gas use, peaking later than CO and NO_x and settling into a modest plateau once gas-chain integrity improves.

From a system perspective the four charts illustrate a credible, infrastructure-constrained decarbonization path. The period between 2030 and 2040 aligns with three shifts visible in Figures 17–20: reduced dispatch of steam turbines, far fewer hours on oil-fired peakers, and incremental renewable additions that shave fossil peaks. By 2045–2050 the stacks stabilize across all four pollutants; CO_2 drifts down gently, CO and NO_x sit well below their 2025–2030 highs, and CH_4 levels off at a limited contribution consistent with an efficient gas backbone. The policy headroom is also evident in the figures: pushing oil dispatch lower, accelerating end-of-life for steam units, and pairing CCGT with tighter gas-leak management would pull Figure 18 and Figure 20 closer to their ADS/LESS profiles and would bend Figure 17 further downward, all without assuming an abrupt technology overhaul.

Chapter 6: Conclusion

6.1 Introduction

This section summarizes the findings from the scenario analysis, presenting the most credible pathway for Bangladesh's electricity future. The analysis highlights the need for a moderated transition that balances efficiency improvements, renewable energy integration, and grid modernization to avoid overstretching the system's capacity.

6.2 Credibility of the Moderate Transition Scenario (MTS)

The scenario analysis shows that Bangladesh's electricity pathway is most credible when it follows a moderated transition that steadily improves efficiency, adds renewables, and fixes grid bottlenecks before pursuing very high variable renewable shares. This conclusion is consistent with the Mujib Climate Prosperity Plan, which frames a practical trajectory toward about 30 percent renewable energy by 2030 and a pathway toward 40 percent by 2041, contingent on grid modernization and investment. [22] In our modelling, the Moderate Transition Scenario (MTS) mirrors this pacing by raising renewable penetration and efficiency while avoiding abrupt technology shifts that would strain the system's current operational limits.

6.3 Alignment with National Commitments

National commitments further support a calibrated approach. Bangladesh's updated NDC projects total emissions of roughly 409 $MtCO_2e$ by 2030 in a business-as-usual case and sets out achievable mitigation under domestic measures and deeper cuts with international support, with the great majority of reductions expected from the energy sector [23]. Anchoring electricity planning to this envelope favors an MTS pathway that expands renewables and efficiency at a rate consistent with financing and system readiness, rather than an accelerated push that risks implementation gaps.

6.4 System Realities and Operational Constraints

The findings from independent assessments of Bangladesh's energy system emphasize several critical issues: surplus installed capacity, low utilization, and rising costs from capacity payments. These challenges cannot be addressed by simply switching from coal to LNG; rather, they require least-cost additions, better use of existing assets, and enhanced transmission and distribution infrastructure to accommodate a higher share of renewable energy [24]. These insights strongly support our MTS, which focuses on improving grid connectivity and system efficiency before scaling up renewable energy at a sustainable pace. By addressing operational constraints first, the MTS ensures that renewable energy integration is both feasible and cost-effective.

6.5 The Feasibility of MTS

Considering all the evidence, the **Moderate Transition Scenario (MTS)** emerges as the most feasible near- to mid-term option for Bangladesh. It supports renewable energy and efficiency improvements in line with national plans, respects the emissions envelope outlined in the NDC, and directly addresses the operational constraints identified by power-sector reviews. By avoiding an overly ambitious and accelerated transition, MTS ensures that Bangladesh can expand renewable energy capacity without risking grid instability or financial strain.[20] [22] [23] [21].

6.6 Comparison with Other Scenarios

While the Accelerated Development Scenario (ADS) presents a more ambitious future, it serves as a stretch case for later years when grid upgrades, storage solutions, and ancillary services are fully developed. The Low Emission Sustainability Scenario (LESS) provides a useful benchmark for long-term ambition but would require significantly stronger external financing and rapid institutional reforms to be credible on today's timelines. The Business-as-Usual (BAU) scenario, on the other hand, highlights the costs and risks associated with delaying the transition, offering a counterfactual that underscores the urgency of moving forward with modernization efforts.

In conclusion, the Moderate Transition Scenario (MTS) offers the most practical, credible, and sustainable approach for Bangladesh's electricity sector in the near and mid-term. It strikes a balance between renewable energy expansion, energy efficiency, and addressing the operational constraints of the existing system. The scenario is well-aligned with Bangladesh's national climate and energy commitments, and it positions the country to meet future electricity demand while minimizing emissions. The MTS also provides a solid foundation for future energy transitions, offering a viable pathway toward a low-carbon energy system.

6.7 Future Direction

Future work should translate the Moderate Transition Scenario into a time-sequenced program. Immediate priorities are grid reinforcements on congested corridors, substation automation, advanced metering in urban feeders, and updated grid codes so variable renewables can connect with minimal curtailment. Pilot storage at renewable hubs, flexible operation of existing gas units, and a clear ancillary-services framework will firm VRE and stabilize frequency and voltage. On the demand side, refreshed efficiency standards for ACs, motors, refrigeration and lighting, plus time-of-use tariffs and industrial demand response, can flatten peaks and reduce the need for expensive peaking assets. Competitive auctions for solar, wind, and solar-plus-storage, paired with standardized interconnection rules and pragmatic net billing for rooftop systems, will provide a predictable pipeline and lower costs.

Over the medium term, planning discipline and financing will determine execution quality. A rolling least-cost plan updated annually should link new capacity approvals to loss reduction, utilization, and reserve margin targets while retiring chronically underused liquid-fuel units and renegotiating costly capacity terms where possible. Regional power trade, selective gas reliability upgrades, and blended finance for grid and storage can improve security and affordability during the scale-up. A public system-operations data platform and targeted training for utilities and regulators in market operations and protection and control will build the capabilities needed to lift MTS toward more ambitious renewable shares once the grid is read.

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